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FINAL PROPOSAL

TRANSIT SOURCES OF SALINITY LOADING IN THE SAN RAFAEL RIVER, COLORADO RIVER BASIN, UTAH

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1.0 Introduction

1.1 Description of the Problem

The Colorado River Basin covers approximately 246,000 square miles over seven southwestern states of the United States and of northwestern Mexico (figure 1. Colorado River Basin Map). Salinity loading in the

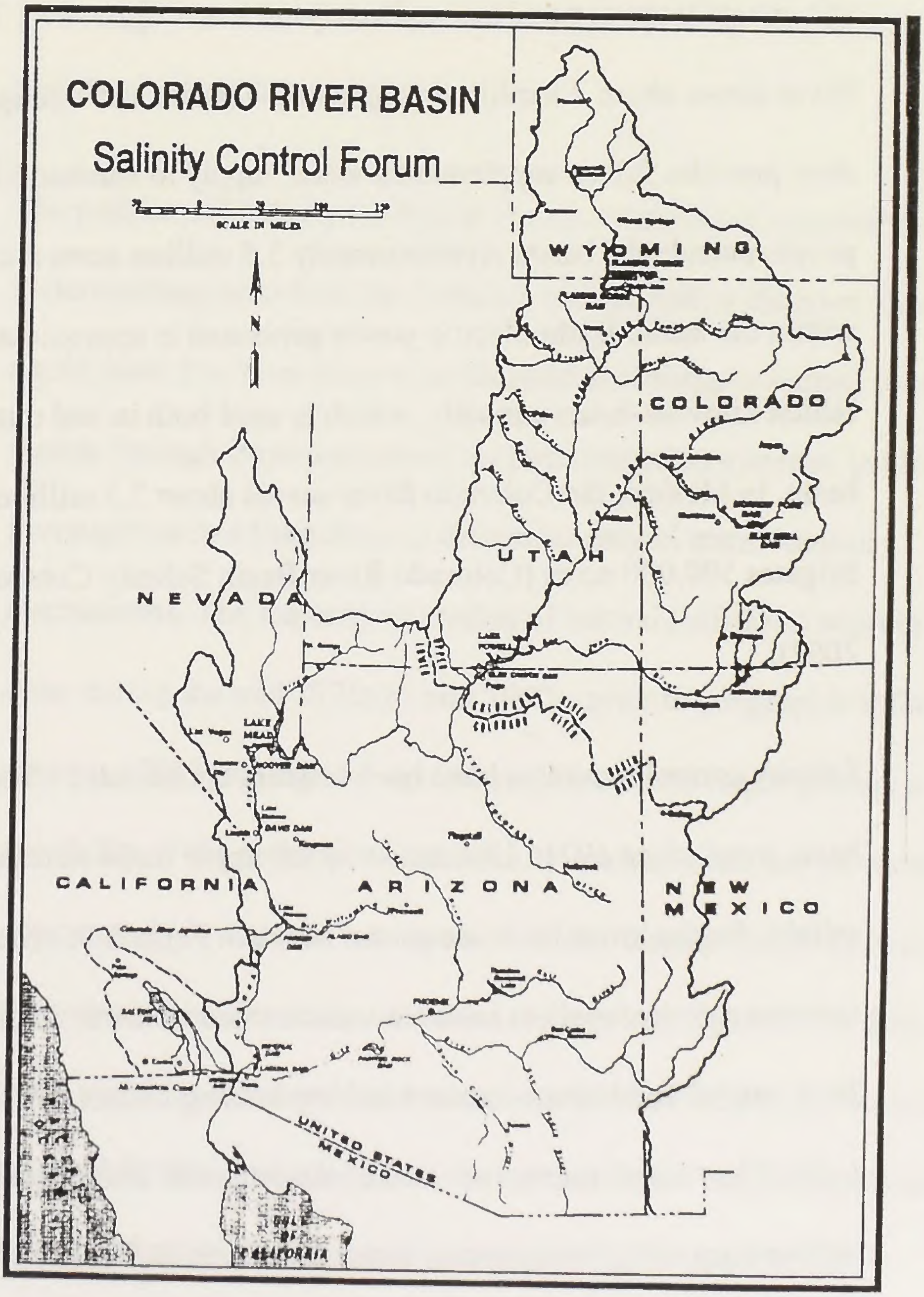


Figure 1. Colorado River Basin Map (from Colorado River Basin Salinity Control Forum 2002 Review Water Quality Standards for Salinity - Colorado River System).

Colorado River is a major concern as the water is a primary source of irrigation and drinking water for the lower basin states (Arizona, Nevada, and California). The upper basin states (Wyoming, Colorado, Utah, and New Mexico) use the river water mainly for irrigation and hydroelectric power. On average (based on about 30 years of data), nine million tons of salt annually travel past Hoover Dam (near Las Vegas, NV). The Colorado River serves about 7.8 million people in the basin, and through export, the river provides full or supplemental water supply to another 23 million people outside the basin. Approximately 3.5 million acres are irrigated within the basin. Hydroelectric power generated is approximately 12 billion kilowatt-hours annually, which is used both in and outside the basin. In Mexico, the Colorado River serves about 2.3 million people and irrigates 500,000 acres (Colorado River Basin Salinity Control Forum, 2002).

Salinity control measures have been actively coordinated among all seven basin states since 1974. Utilization by the upper basin states can increase salinity for the lower basin states and Mexico. Periods of drought can increase salinity levels as salts are concentrated in lower volumes of water. Both natural and human-induced salinity loading occurs throughout the basin. The natural sources are mainly decomposed sediments from sedimentary rock formations of late Paleozoic (e.g., Pennsylvanian Period – Paradox formation (fm.)), Mesozoic (e.g., Triassic – Moenkopi fm., Jurassic – Summerville and Curtis fms., and Cretaceous – Mancos Shale fm.) and early Cenozoic eras (e.g., Green River fm.) that contain sodium-, calcium-, and magnesium-sulfate, chloride and carbonate salts (Chronic, 1990). The human sources are mainly from irrigation return flows, where salts have concentrated in the water. There is recent concern that coal-bed methane development and its associated brine-water disposal could increase future salinity loading in the upper basin (Colorado River Basin Salinity Control Forum, 2002).

The problem of salinity loading to the Colorado River involves a lack of understanding as to how the loads are transported to the river. Much useful work has been done to understand and mitigate human sources – mainly through improvement of on-farm irrigation systems, but less investigation has been done to determine natural transit-source mechanisms. The majority of studies of natural (off-farm) sources were done during the mid 1970s to mid 1980s, prior to geographic information systems (GIS) gaining widespread use. One of the major powers of GIS is the ability of the software to statistically analyze a number of variables concurrently in a spatial setting and visually display results in overlying map coverages. The study of natural salinity loading involves different basic variables that need to be taken into account. The major variables selected for this study include: location and extent of salt-contributing geologic formations; location, extent, permeability and salinity concentration of soils; geomorphic structures and topographical gradient; ground-water quality and gradient; and meteorologic and climatologic data. GIS allows multivariate correlations to be determined and will illustrate which of the selected natural variables are the most important salinity contributors over different topographical areas. It is with the application of GIS techniques that this research strives to gain better understanding of salinity-loading, transit-source mechanisms.

1.2 Background

1.2.1 **Geographical Setting** – In general, the Colorado River Basin can be separated into the upper basin and the lower basin. The Colorado Plateau physiographic province that covers the eastern half of Utah, western half of Colorado, northern Arizona, and northwestern New Mexico, dominates the upper basin. The lower basin is dominated by part of the Basin and Range province and vast desert valleys that are at a lower elevation than the upper basin plateau region. This research is confined to the upper basin plateau area, as that is where natural sources of salinity loading occur to a much greater extent. On the plateau, decomposing rock formations that contain different types of salts fill many ephemeral and intermittent streambeds with loose sediment. Mainly during the middle to late summer season, monsoonal (cloudburst) storms can move the sediment further down the channels towards perennial streams that feed the Colorado River (Mundorff and Thompson, 1982). This overland movement, which in this study includes ephemeral channel movement, is one major transit-source mechanism. The other major transit-source mechanism involves ground-water movement through or along the top (underground) of salt-bearing formations towards streams (Hood and Patterson, 1984). The ground-water flow will enter streams during spring snowmelt runoff and as irrigation return flows from up-gradient areas (Mundorff and Thompson, 1982).

1.2.2 Administrative Setting

1.2.2 Administrative Setting - The Colorado River Board of California recognized back in 1956, when Congress passed the Colorado River Storage Project and Participating Projects bill, that construction of large dams, reservoirs, and hydroelectric generating plants would likely increase the salinity of water flowing downstream for irrigation and public supply. The 1922 Colorado River Compact apportioned water throughout the upper and lower basins, but made no explicit provision regarding water quality. Hence, in 1966 representatives of the seven basin states began to meet to create guidelines so that water-quality standards, being developed separately in each state, would be mutually compatible. Then, in 1969, the Chief Engineer of the Colorado River Board of California formally requested that policy be developed to begin a salinity control program and to develop numerical salinity criteria for incorporation as part of each basin state's water-quality standards (Colorado River Board of California, 1970).

The Clean Water Act, which designates maintenance of water-quality standards in the United States (USA), was signed into law in 1972. During this same year the USA and Mexico had been discussing the increasing salinity of the Colorado River water that came into Mexico. Congress created the Colorado River Basin Salinity Control Forum (the Forum) in 1973 to address salinity control through interstate cooperation and to provide information to the Department of the Interior that would show efforts and steps taken toward compliance with Section 303(a) and (b) of the Clean Water Act. Congress enacted the Colorado River Basin Salinity Control Act in 1974 (Public Law (P.L. 93-320)) Title I, which states the USA's commitment to Mexico for water deliveries, and Title II, which creates a salinity-control program for the river. Then the Environmental Protection Agency (EPA) promulgated a basin-wide, salinity-control regulation in late 1974. This regulation established a standards procedure, which required the seven basin states to adopt and submit for approval to the EPA water-quality salinity standards, including numeric criteria for the river. In 1984, the Salinity Control Act was amended, in part, to direct the Bureau of Land Management (BLM) to implement a comprehensive program to minimize salt loading in the Colorado River basin and to establish a voluntary, on-farm salinity control program to be implemented by the U.S. Department of Agriculture (USDA).

Funding for salinity projects comes through the USDA (Farm Bill Environmental Quality Incentives Program - EQIP monies) and the expenditure of those funds are regulated by the Bureau of Reclamation (BOR). Official salinity evaluations are made by the BOR, U.S. Geological Survey (USGS), and the BLM (Colorado River Basin Salinity Control Forum, 2002).

1.3 Research Objective

The objective of this study is to develop and test a methodology for determining the major transit source of salt loads (surface-water runoff or ground-water inflow to the stream), that takes into account the potential of the salt loads to reach perennial streams, and quantifies those salt loads in the San Rafael River, a tributary to the Green River which flows into the Colorado River in Utah.

This proposed methodology is transferable to other Colorado River watersheds, and if utilized prior to developing salinity-control projects, will allow for a more correct expenditure of planning, design, and construction monies.

1.4 Organization of Proposal

This proposal begins with a general description of the Colorado River Basin and the overall problem of salinity loading to the river throughout the basin. Section 1.0 gives the general background setting, both the geographical and administrative history. The particular research objective is stated to delineate the reason for this study. Section 1.0 ends with a description of the structure of the whole proposal. Section 2.0 covers past research to inform the reader of other Colorado River Basin salinity-loading studies and their particular objectives. Major differences between this study and past studies are stated to explain why this new proposed study should be conducted. Section 3.0 gives more detail regarding the study including: the questions this study will attempt to answer; the general hypothesis (knowledge) of salinity loading that is a finding of most studies; the conceptual structure or framework of this research; and finally, physiographic particulars on the study's location. Section 4.0 explains the proposed methodology. Factors that will be measured and their relevance to the methodology are described. The spatial aspects of this study are explained in terms of these selected factors. Section 5.0 goes through the basic science techniques that will be used to measure the selected factors. Each technique's importance, in terms of the whole study, is stated in this section. Section 6.0 describes the analyses that will be conducted to assess, compare, and contrast the different types of measurements. There are 2 main types of analyses: statistics and GIS. Statistics will be done with and without GIS analysis. The analyses are explained in terms of what the researcher is attempting to understand and answer. The interpretation from the analyses is the last step of the proposed methodology. Section 7.0 is a time-line table of the proposed tasks that comprise the methodology and Section 8.0 lists all of the researcher's cited references.

2.0 Past Research

2.1 Overview

Over the past 50 years the majority of studies have focused on surface-runoff transit sources, but beginning in the mid 1980s, two U.S. Geological Survey investigations gathered evidence that attribute larger than previously thought amounts of salt from ground-water inflow systems to the streams in the Colorado River basin (Warner and others, 1985, and Westenburg, 1995). Also, a PhD dissertation was completed in 1984, which investigated ground-water salinity loading in the Colorado River basin from the Mancos Shale formation (Deyo, 1984). Studies conducted from about 1978 on in Australia have investigated ways of locating and characterizing areas of subsurface saline soil (Williams and Braunach, 1983) utilizing exploration drill holes or much less expensive electromagnetic induction soil surveys. In summary, considering the two major transit sources of salt loading to a perennial stream: surface-water runoff processes and ground-water inflow processes; most work to date in the Colorado Plateau has focused on surface-water runoff processes, and a lesser amount of work has been done to investigate ground-water inflow processes, the factors that determine which major process will occur, where susceptible areas are for each process, and the quantification of loads attributed to each process.

2.2 Literature Review of Past Studies

A total of 58 applicable sources were reviewed for this study. The breakdown is as follows: 25 Federal and State investigation reports; 18 journal articles, Utah Water Research Lab, and Utah Agricultural Experiment Station reports; 4 M.S. theses; 5 Ph.D. dissertations; and six textbooks – 2 geology and 4 statistical texts. Of the 58 sources, 24 were selected and summaries were written (available in appendix A). The selected summaries included all of the M.S. theses and Ph.D. dissertations, 9 journal/Water Research Lab/Agricultural Experiment Station papers, and 6 Federal/State investigations. These sources were selected for written review for a number of reasons including: 1) salinity studies done in the Colorado Plateau; 2) factors studied/methods used that are common to this study; 3) particularly interesting results; and 4) important data compilations. Chronologically for the written summaries: one study was conducted in the 1950s, eight were done in the 1970s, nine in the 1980s, four in the 1990s, and two after the year 2000. However, the bulk of the studies, which have written reviews, were published during a ten-year period between the mid 1970s and the mid 1980s. The important point of this heavy publishing period is that geographic information systems (GIS) such as Arc Info/Arc View were not widely used until later. Most of these salinity studies could have benefited greatly from GIS mapping and analysis. Of all 58 sources, only one study used GIS and for the mapping capability only – not analysis (reference Miller, 2002). Many of the studies used statistics and some of the studies used flow and/or geochemical software models to investigate the salinity data.

2.3 Differences in Terms of This Study

Selected written reviews available in Appendix A go into detail on the differences in terms of this study. However, in general, two areas predominated: 1) objectives of the study, and 2) absence of GIS analysis. This study creates a methodology that determines the transit source of salinity loading to a perennial stream. Transit source is either an overland runoff process or it is a ground-water inflow process. Of the 24 written reviews, 17 were studies of salinity problems/questions (e.g., sediment yields, division of agricultural versus natural runoff, geomorphic controls on overland flow, channel evolution, geochemical fate and transport modeling of the salts, climatic controls on streamflow and sediment runoff, runoff and water quality of different Mancos shale landforms, sedimentation in small reservoirs, salt dissolution kinetics, etc.). The remaining seven studies were mainly statistical characterizations of large data sets, some with trend analysis. One difference is that the reviewed studies often investigated some, but not all of the factors this study will take into account for determining the major mode of salt transport in a watershed. This study will analyze not just water chemistry data, or geomorphic landforms, or soil surveys, or soil chemistry, or amounts and intensities of rainfall, but all of them together. The other major difference is that this study will utilize both the mapping and analysis capability of GIS to compile and analyze all these factors. As mentioned earlier, with the exception of Miller's 2002 study, which used GIS for mapping, none of the other reviewed studies utilized GIS.

3.0 New Research Design

3.1 Major Research Questions

How does the salt get into the river? That is the research question stated in a simple manner, but the search to the answer is much more complex as are most quests to understand environmental processes. There are two general travel modes or transit sources: 1) Overland or surface-water flows, and 2) Ground-water inflows to the river. Some studies break out a third mode called in-channel flow, but in this study it will be grouped with surface-water flows. In order to develop a transferable methodology that determines major transit-source mechanisms and that takes into account the potential of salt loads reaching the stream, then goes about quantifying those loads in the stream, it is important to recognize the science is interdisciplinary in nature and involves to the greatest extent soil and water parameters. Some studies bring in a vegetation factor, as plants in semi-arid environments can often concentrate the salts in soils near them. The objective here is to decide the watershed is either most prone to overland flow, or most prone to ground-water inflows, thus vegetation is not as important a factor as soils. However, vegetation will be investigated to characterize what types exist in the watershed and their evapotranspiration rates. Vegetative matter can also retard the movement of overland flow and so it also needs to be assessed for this reason.

3.2 General Hypothesis of Salinity Loading

The initial hypothesis is that rocks and soil with higher amounts of clay will retard ground-water movement toward the stream; hence, these are probably areas of more surface-runoff contribution. If these soil types are also high in salts and/or have developed a thin surface layer of efflorescent salts, then the surface runoff will have a higher salinity, often with the largest amount of salt coming off during the first rain after a long dry period. If a perennial stream is nearby, the salts should show up in adjacent stream water. If there is not a perennial stream nearby, often the salt loads will get dropped sooner in ephemeral channels. Soils that contain higher amounts of sand and silt and show high amounts of salts in adjacent stream water are probable areas of salinity loading from ground-water movement into streams. These permeable soils, most likely, are not the source soils for salinity, but rather, only a ground-water pathway. The sandy soils could be sitting on top of the more clayey shale, and then ground water will leach the salts from the clay layers as it moves along the top of the more impermeable surface until it seeps into the stream in a gaining area. Soil-salt concentrations and contributing area are important factors.

3.3 Framework of Research

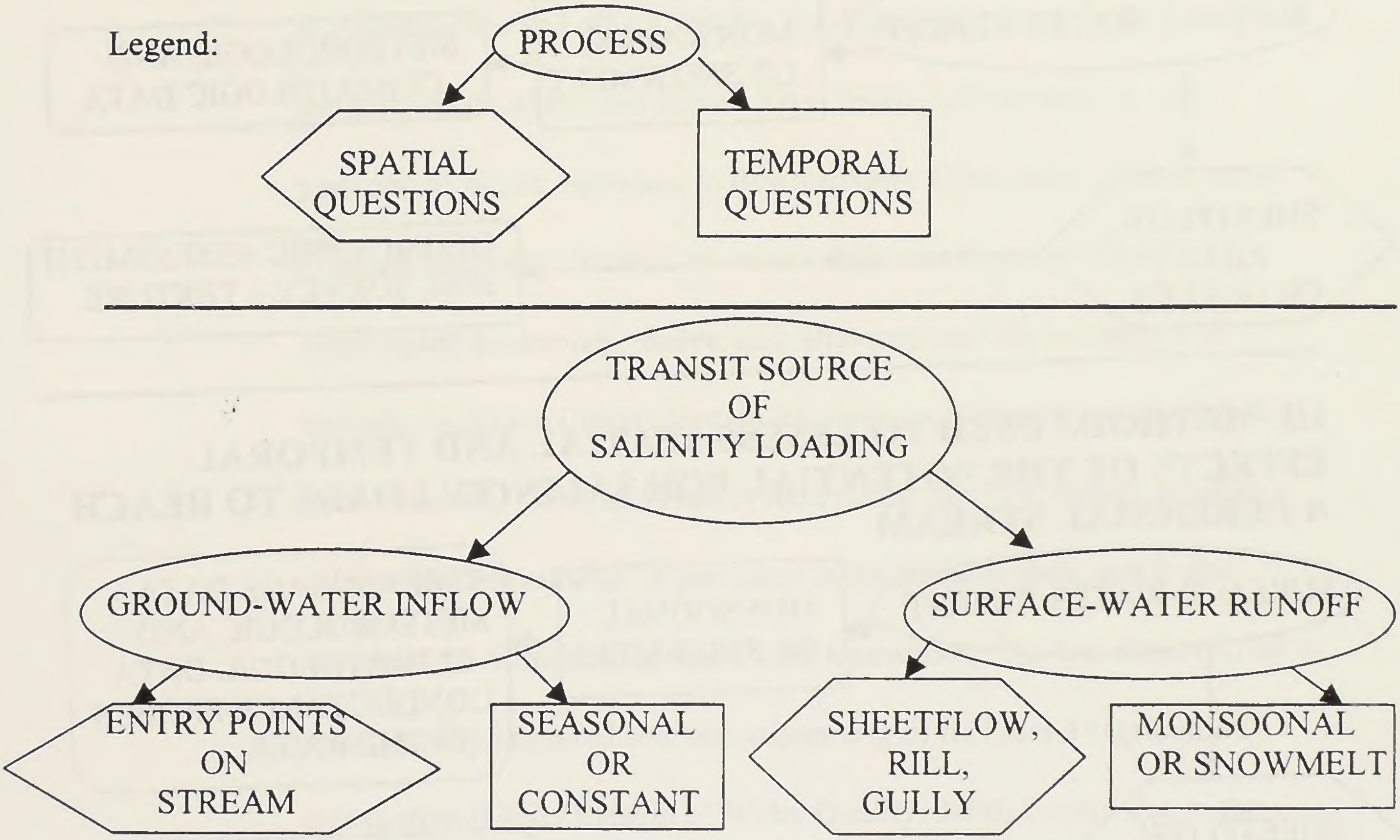
Figure 2 illustrates in flow-chart form the basic structure of this research. The overall problem is determining the major transit source of salinity loading, which breaks down into ground-water inflow and surface-water runoff processes. For each of those processes, there are spatial and temporal effects and questions to be answered. The ground-water inflow process could be seasonal (spring) or almost year-round. Soils developed from different types of underlying geologic formations will allow some areas of the stream to become entry points for the ground-water inflow (e.g., sandy and sandy/silty soils). The surface-water runoff process usually occurs during monsoonal (convective) storms in mid to late summer in the Colorado Plateau watersheds, but depending on the amount of snowmelt, overland flows can also occur during spring runoff. When overland flows do occur, the water traverses the ground several different ways: via sheetflow, creating rill patterns, or by erosive gullying. Some of the influencing factors of how the water will travel over the land usually include geomorphic structures, topographic gradient, and type of soil. The second part of the Framework of Research figure illustrates the methods used to assess spatial and temporal effects of transit-source loading. The discussion for these methods is below in section 4.0 Methodology.

3.4 Study Location

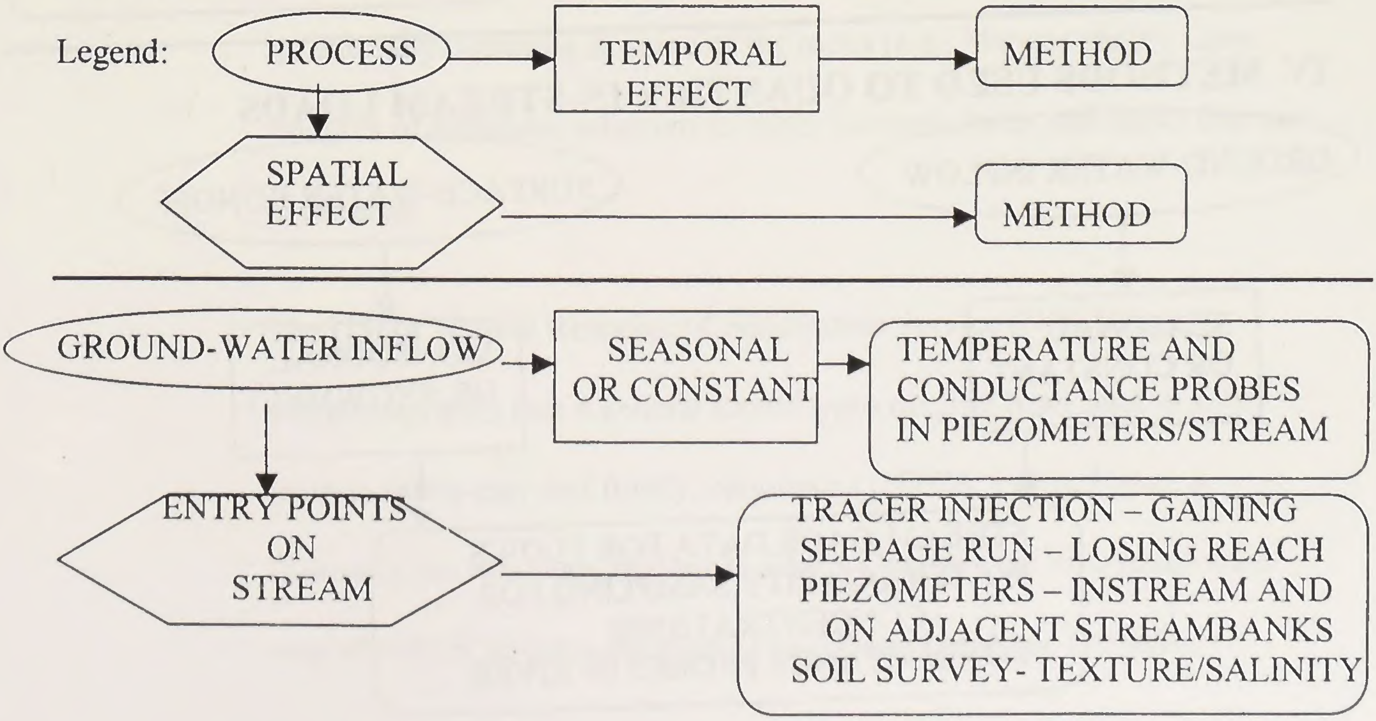
FIGURE 2

FRAMEWORK OF RESEARCH

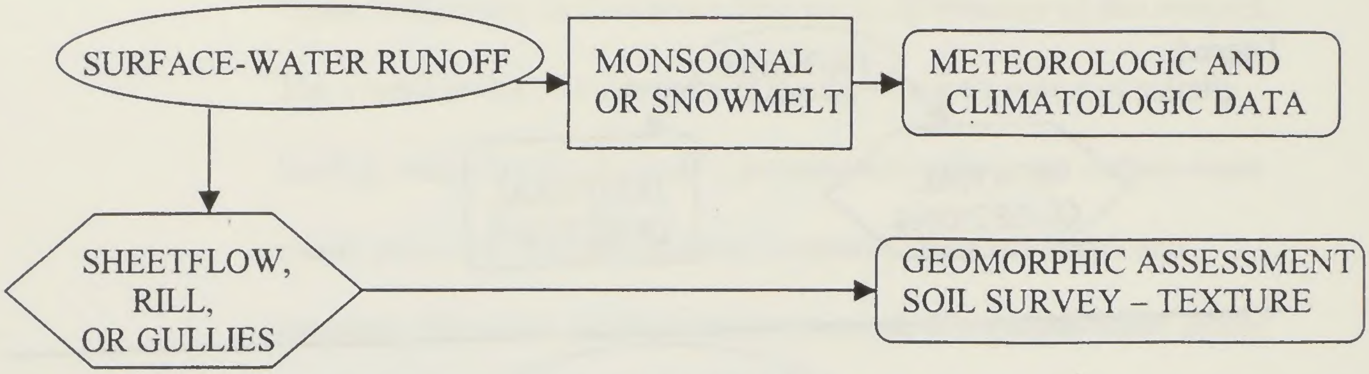
I. SPATIAL AND TEMPORAL EFFECTS OF TRANSIT SOURCE LOADING PROCESS



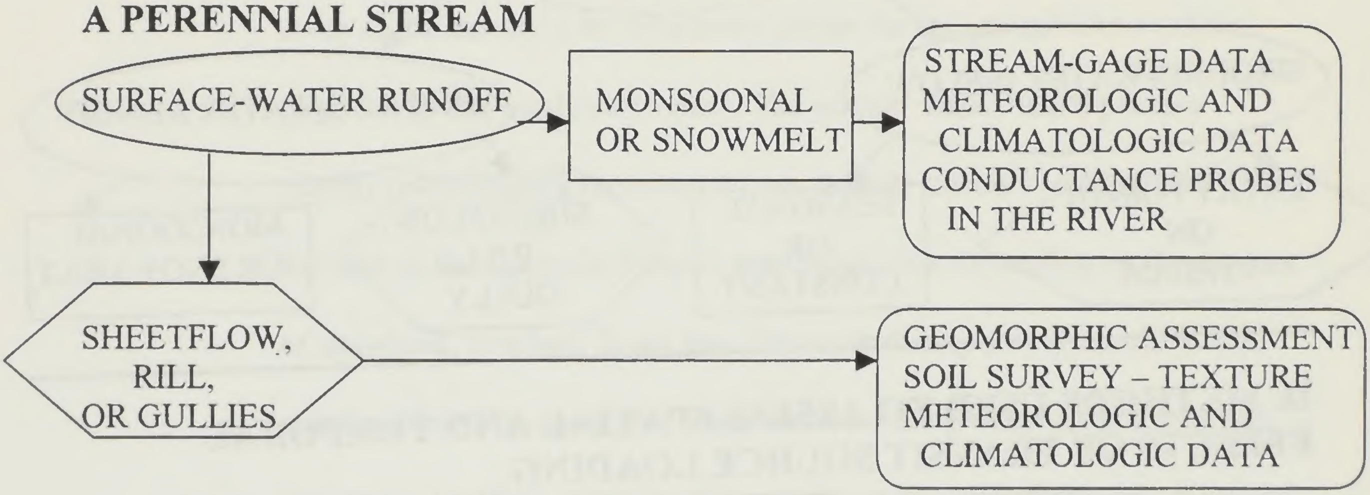
II. METHODS USED TO ASSESS SPATIAL AND TEMPORAL EFFECTS OF TRANSIT SOURCE LOADING


Legend:
PROCESS
TEMPORAL EFFECT
METHOD
SPATIAL EFFECT
METHOD
GROUND-WATER INFLOW
SEASONAL OR CONSTANT
TEMPERATURE AND CONDUCTANCE PROBES IN PIEZOMETERS/STREAM
ENTRY POINTS ON STREAM
TRACER INJECTION – GAINING
SEEPAGE RUN – LOSING REACH
PIEZOMETERS – INSTREAM AND ON ADJACENT STREAMBANKS
SOIL SURVEY- TEXTURE/SALINITY

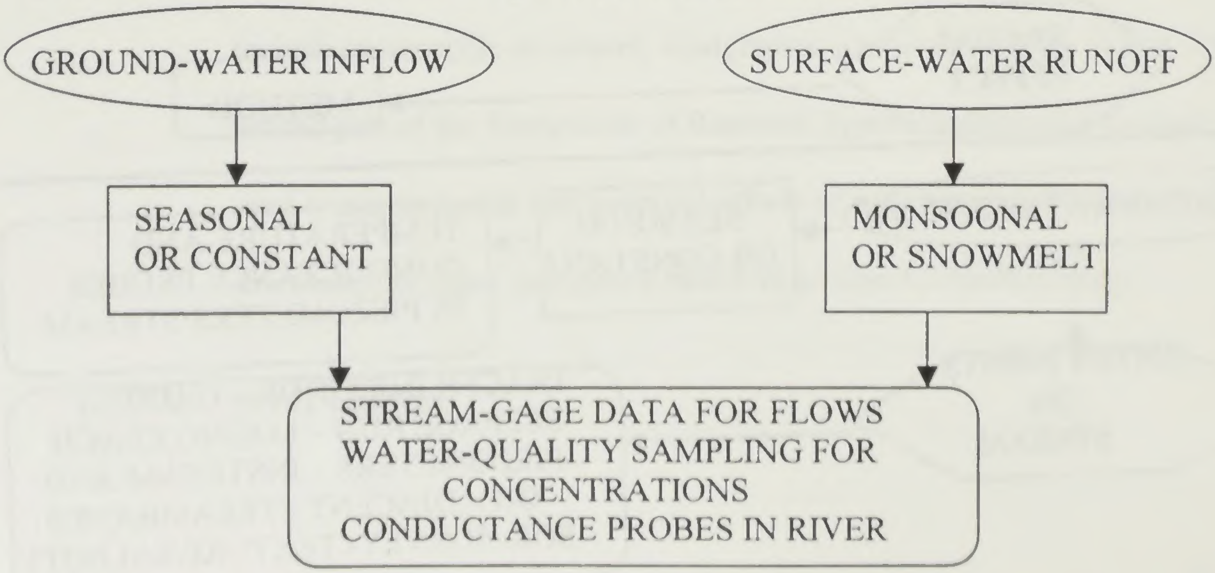
II. METHODS USED TO ASSESS SPATIAL AND TEMPORAL EFFECTS OF TRANSIT SOURCE LOADING – Continued


SURFACE-WATER RUNOFF
MONSOONAL OR SNOWMELT
METEOROLOGIC AND CLIMATOLOGIC DATA
SHEETFLOW, RILL, OR GULLIES
GEOMORPHIC ASSESSMENT SOIL SURVEY – TEXTURE

III. METHODS USED TO ASSESS SPATIAL AND TEMPORAL EFFECTS OF THE POTENTIAL FOR SALINITY LOADS TO REACH A PERENNIAL STREAM

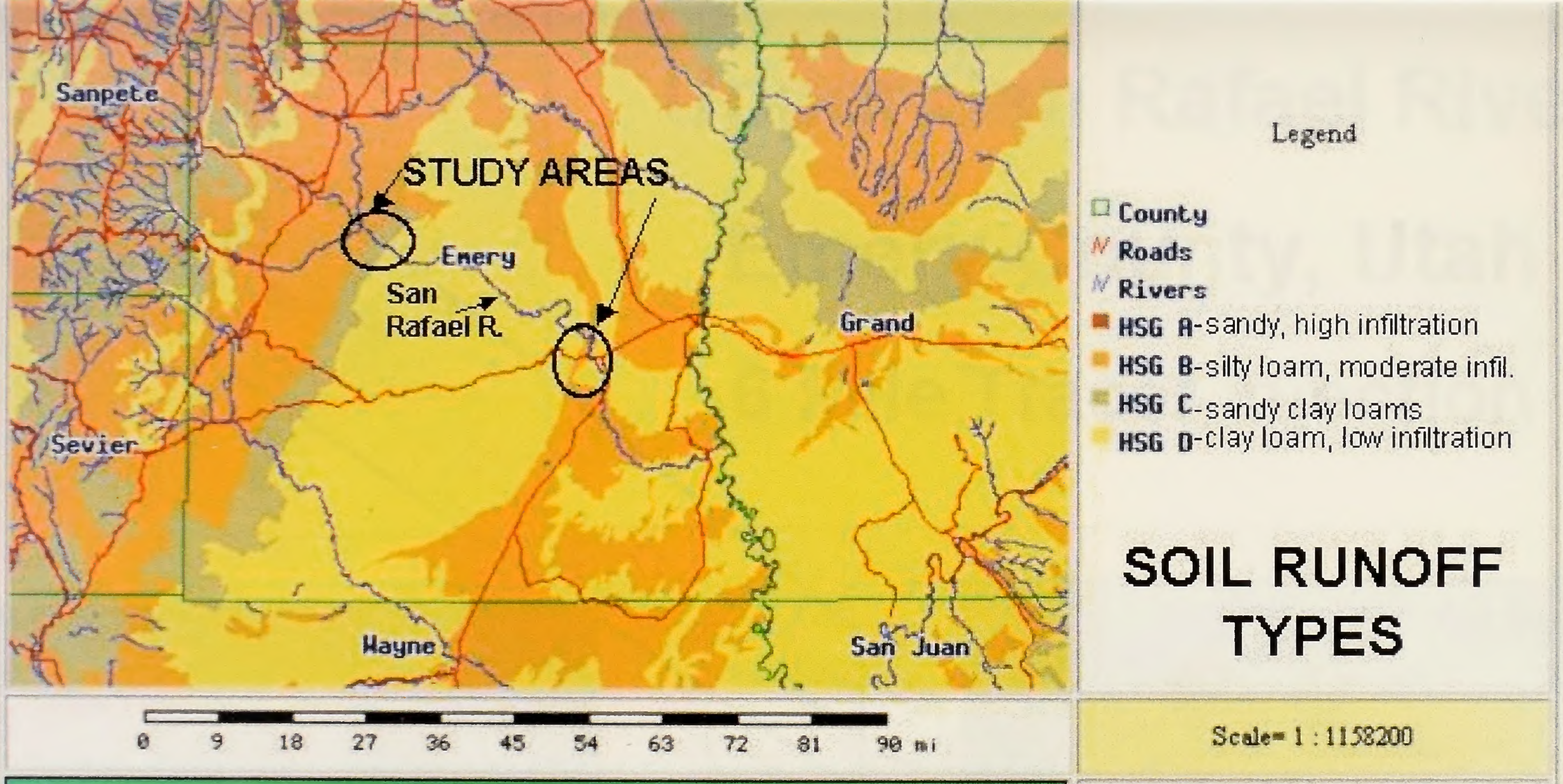

SURFACE-WATER RUNOFF
MONSOONAL OR SNOWMELT
STREAM-GAGE DATA METEOROLOGIC AND CLIMATOLOGIC DATA CONDUCTANCE PROBES IN THE RIVER
SHEETFLOW, RILL, OR GULLIES
GEOMORPHIC ASSESSMENT SOIL SURVEY – TEXTURE METEOROLOGIC AND CLIMATOLOGIC DATA

IV. METHODS USED TO QUANTIFY IN-STREAM LOADS


GROUND-WATER INFLOW
SURFACE-WATER RUNOFF
SEASONAL OR CONSTANT
MONSOONAL OR SNOWMELT
STREAM-GAGE DATA FOR FLOWS WATER-QUALITY SAMPLING FOR CONCENTRATIONS CONDUCTANCE PROBES IN RIVER

The Colorado River Basin is in the Colorado Plateau physiographic province. The San Rafael River is in the Canyonlands sub-division of this province (Lines and others, 1984). Geologic formations that occur within the headwaters of the San Rafael River basin include (west to east, youngest to oldest, upstream to downstream): Cretaceous Mancos shale (Tununk member); Jurassic Morrison shale and Summerville/Curtis interbedded mudstones, shales, and siltstones; and the red ledges of Entrada sandstone (Intermountain Association of Petroleum Geologists, 1954, Chronic, 1990, and Hadley field notes, 2002). Gypsum, a hydrous calcium-sulfate mineral, is prevalent in the Mancos shale and it also occurs in the Summerville and Curtis formations. The San Rafael River is water-quality impaired and non-supporting of its Class 4 (agricultural) designation (Utah Division of Water Quality, 2000) largely due to the dissolution of calcium sulfate (i.e., gypsum), and sodium and magnesium sulfates creating high levels of total dissolved solids. Also, selenium salts are naturally occurring in some of the rocks (e.g., Mancos shale). Large amounts of dissolved selenium in water can harm birds and ducks that nest in the area.

The USDA Natural Resources Conservation Service (NRCS) has categorized soils into 4 general runoff types ranging from sand to silty-loam to sandy-clay and finally, clay-loams (NRCS, 1986). Figure 3 illustrates the two study reaches in Emery County Utah on a small-scale map of NRCS' soil run-off types. The different geologic formations


Sanpete
STUDY AREAS
Emery
San Rafael R.
Grand
Sevier
Wayne
San Juan
Legend
☐ County
Roads
Rivers
HSG A-sandy, high infiltration
HSG B-silty loam, moderate infil.
HSG C-sandy clay loams
HSG D-clay loam, low infiltration
0 9 18 27 36 45 54 63 72 81 90 mi
Scale= 1 : 1158200

SOIL RUNOFF TYPES

2 San Rafael River reaches:

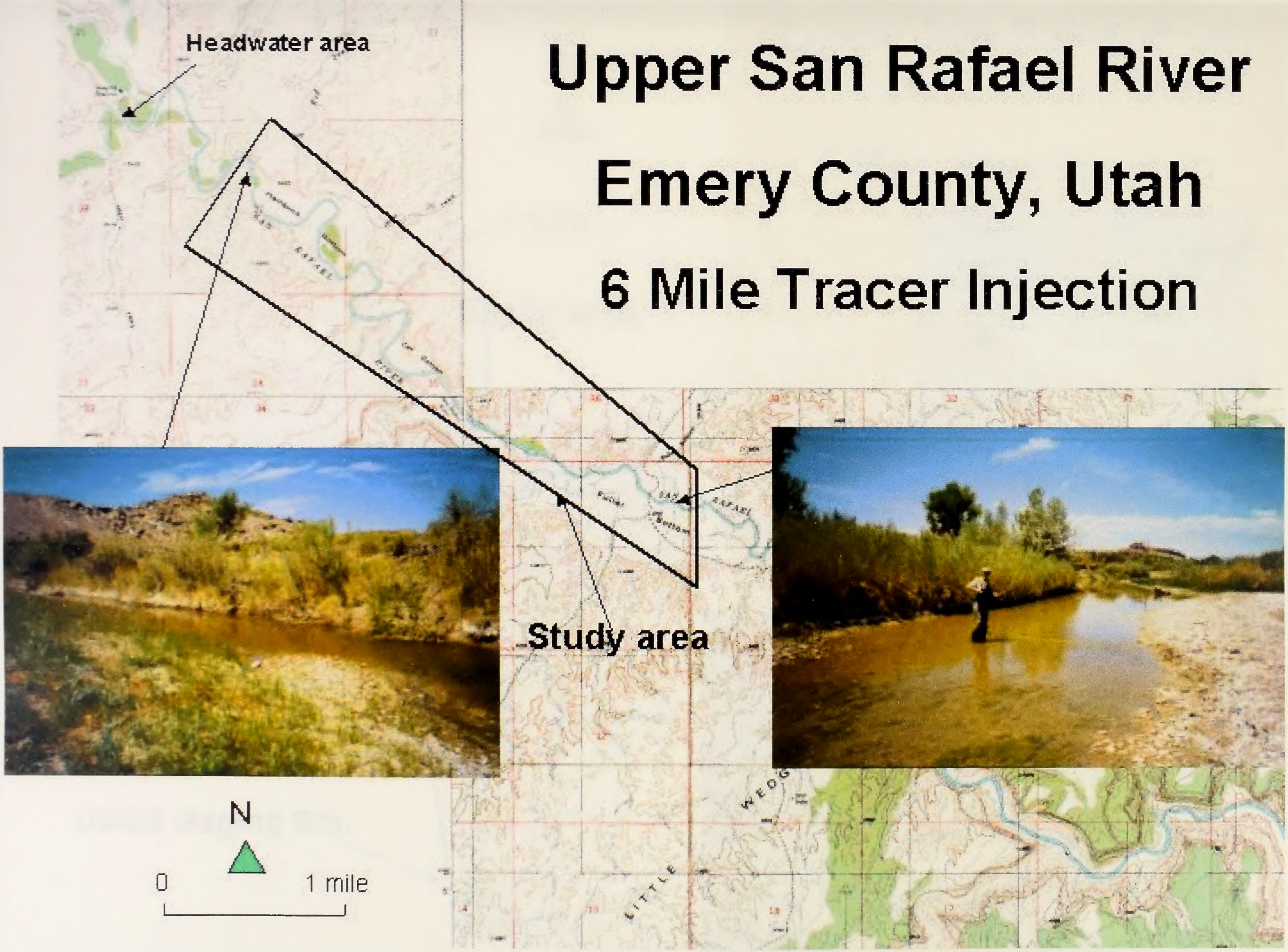
Upper reach – gaining

Lower reach – losing

Upper San Rafael River

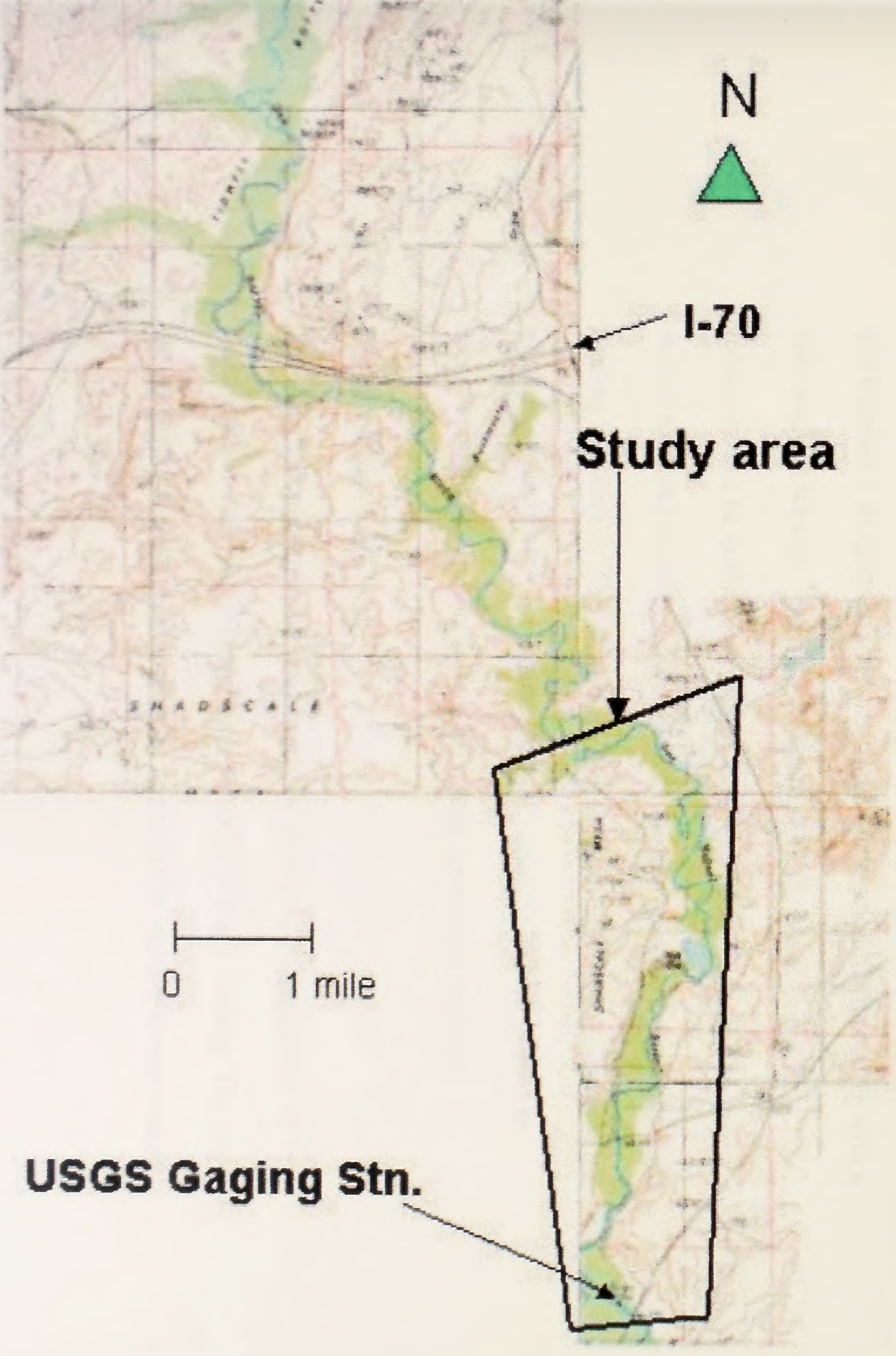
Emery County, Utah

6 Mile Tracer Injection



Lower San Rafael River
Emery County, Utah

6 Mile Seepage Run



decompose into soils and those soils will generally fit into one of the 4 soil-runoff categories.

Two study reaches, a gaining reach near the headwaters of the San Rafael River and a losing reach near the confluence of the San Rafael and Green Rivers, have been chosen to develop the methodology of investigating salt loading in the watershed (figures 4 and 5).

4.0 Methodology

4.1 Overview

The objective of this study is to create a methodology, so in a sense, the methodology is the 'means' and the 'end'. The concept of the 'end' is to put together a program of the most appropriate scientific measures with a GIS analysis scheme. The data collected from the set of scientific measures will be analyzed in GIS to identify important combinations of factors that lead to either surface-water runoff or ground-water inflow salt loading to a stream. The 'means' (reference second half of figure 2) is the purpose of the scientific measures and GIS analysis, which is used to assess spatial and temporal effects of transit-source salt loading.

4.2 Factors Measured

The scientific measures are used to gather evidence, for or against, of either surface-water runoff or ground-water inflow salt loading. The major factors assumed to be most important to this study include stream-water chemistry and flow, ground-water chemistry and gradient, soil chemistry and texture analysis, rock compositions, geomorphic features, topographic gradients, precipitation data, and climatologic history.

4.3 Relevance of the Factors

Stream-water chemistry and flow: The salt load in the stream is the problem. The water is used downstream (Colorado River end-users) for drinking water and irrigation. So, determining the chemistry, or salt-load, will reveal the severity of the problem. Stream-water chemistry changes along the reach will reveal possible areas of either higher or lower total dissolved (TDS) water coming in. The importance of calculating flow is that higher flow most often correlates with larger salt loads (salt concentrations multiplied by flow gives loads).

Ground-water chemistry and gradient: Ground water is part of the hydrologic cycle and is therefore tied to stream water, rainfall, snowmelt, and the human uses of water on the earth (e.g., irrigation return flows). Just as stream water reveals a 'picture' of these influences, so does ground water. The relevance of measuring the chemistry of ground water is to see if there is a correlation to surrounding or adjacent soils and stream-water chemistry. The relevance of establishing the ground-water gradient is to discern the direction ground water is moving, i.e., towards the stream or away from the stream. If it is moving towards the stream, then the gradient makes it possible to deliver salt loads to the stream.

Soil chemistry and texture analysis: The salts in the soil dissolve into the ground and surface waters. So the relevance of determining the soil chemistry is to determine any connections to surrounding or adjacent ground and surface waters. Soil texture analysis is tied to the assessment of mobility of ground water through the soils.

Rock compositions: The underlying rocks decompose and the minerals become part of the soil. Then, the minerals in the soils decompose further upon contact with ground and surface waters. So the rocks are the source of the salts. Knowing the locations, extent and compositions of the various rock formations is the 'base map'.

Geomorphic features: Channel morphology, how the stream channel is shaped and how it moves (bends) across the land, can retard or accelerate the movement of water, affect erosion (e.g., deposition of loads in wide channels or bank cutting in narrow channels), and give 'clues' as to what type of soils the stream is passing through.

Topographic gradients: The angles and lengths of slopes on land surrounding the stream affect not only how water will move to the stream, but possibly the amount of material water will carry with it. The texture of the soil has to be taken in account also – reference the previous discussion on NRCS' soil-runoff types.

Precipitation data: Amount and length of rainfall events need to be correlated with stream-water chemistry and flows to better understand how precipitation affects salt loads in the stream.

Climatologic history: Trend analysis of long periods of precipitation data should be correlated with long-term, stream-load data. One USGS gaging station on the San Rafael River, San Rafael River near Green River, has over 40 years of chemistry and flow data, which will allow this correlation analysis to be performed locally. Other sites outside the local watershed will also be assessed if possible.

4.4 Spatial and Temporal Considerations

All of the above factors carry spatial and temporal considerations. As illustrated on figure 2, if the salt-loading process is ground-water inflow, then entry points along the gaining reach are a concern and need to be located. Often a gaining reach will transform to a losing reach during the summer. This temporal consideration has to be investigated to identify when it happens. The in-stream piezometers described below will illustrate how this can be done. If the salt-loading process is surface-water runoff, then the soil-survey that determines salinity and textures of the soils will be important, as will the geomorphic assessment and topographic gradient determination. (Note: For figure 2, topographic gradient is considered to be part of geomorphic assessment.) Meteorologic and climatologic data are assessed in spatial and temporal terms for the surface-water runoff process. Extent and duration of storms are related to salt loads, but it is a multi-parameter assessment, because soil chemistry and textures, along with geomorphic information, will all be factored in during GIS analysis.

5.0 Measurement Techniques

5.1 Stream Gages

Stream gages record stage height. The channel width is multiplied by the stage height to determine area (square feet) and then multiplied by velocity (feet per second) to determine a flow (cubic feet per second). Both the gaining and losing reaches have stream gages bracketing each reach (total 4). Stage height will go up with snowmelt runoff and storm activity. The recorded data will show when, how long, and what the flows were for each event. The gages also act as control points ('anchors') for the seepage run and tracer injection.

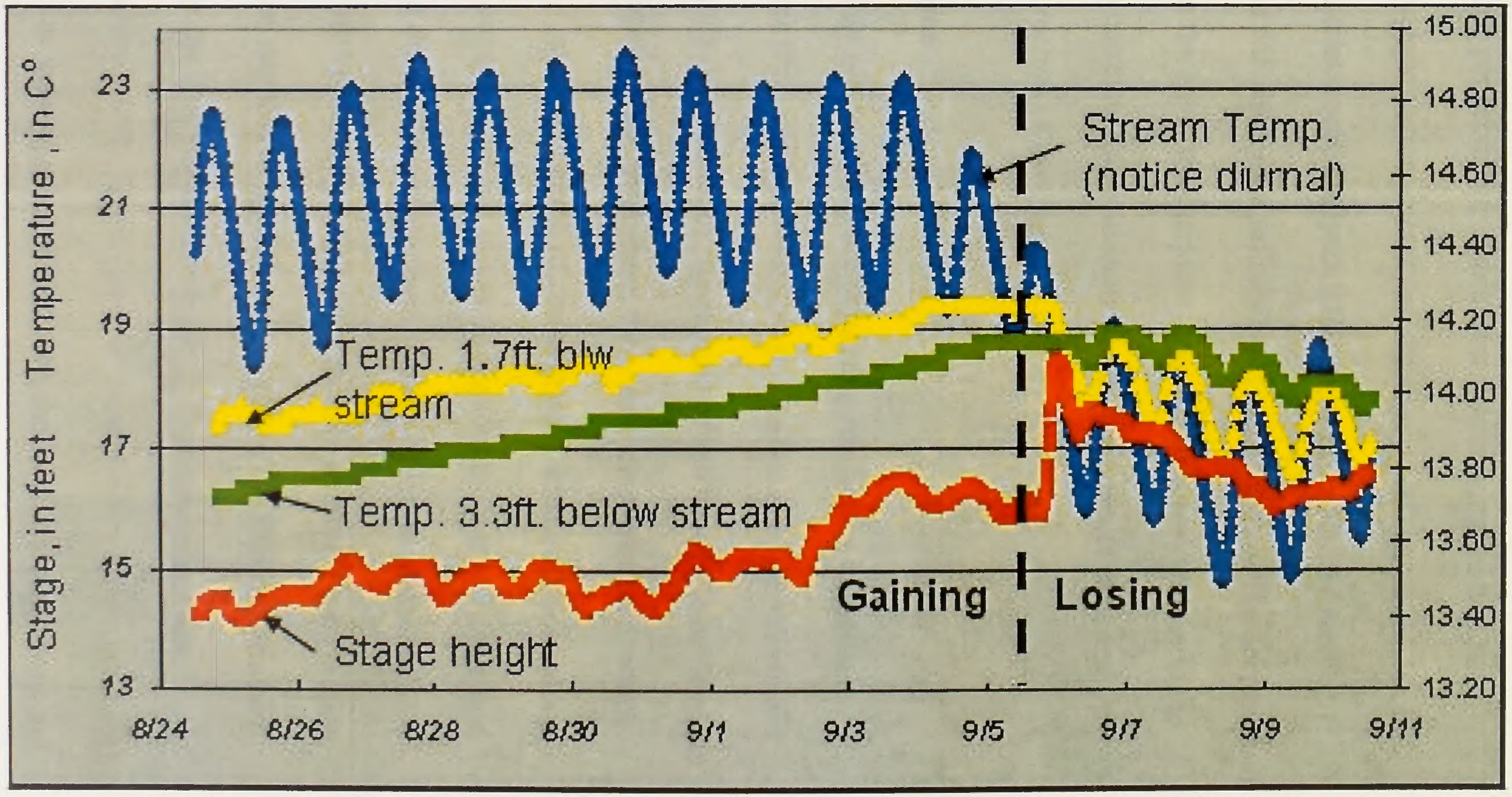
5.2 Piezometers

Piezometers are shallow wells that will be installed in different soil-runoff types on land near the stream in transects perpendicular to the stream. The piezometers with temperature probes will also be installed in the stream in order to assist in determining gaining and losing sections of each reach. Both in-stream and on-land piezometers will be installed to different depths, as there is usually a ground-water temperature gradient. Ground water closer to the surface usually has less of a differential with surface-water and is more affected by the air temperature change from day to night (diurnal). Deeper ground water may have a larger temperature differential from surface water and is less affected by a diurnal change. Figure 6 is a graph illustrating the utility of in-stream piezometers with temperature probes at a USGS study site on the Boise River in Idaho. On the graph timeline, it can be seen from the temperature probe data that this area in the stream changed from a gaining to a losing section near September 6, 2001. The reason, in this case, is attributed to the closing of an irrigation ditch gate, which increased the flow (i.e., raised the stage height) in the main stem of the river. It is thought that the increased flow, which increased pressure, reversed the flow to an outward movement, i.e., it is now a losing stream where the surface-water is going into the ground, instead of the ground water flowing into the stream. It can be seen from this graph that an increase in stage height can reverse flows in the ground near the river. An increase in stage height will often happen during storm events. It will be interesting to see if this happens in the San Rafael River. Ground water in the piezometers will be sampled for major ions and trace metals. These data will be correlated with soil chemistry and adjacent stream-water chemistry. Ground-water levels will also be measured to establish a potentiometric surface, which will help determine flow paths.

5.3 Seepage Run

Stream-water losses to the ground can be calculated by conducting a seepage run. Current-meter measurements are made in a synoptic manner along the study reach. Synoptic is defined as a 'snapshot in time'. In order

Graph of stream stage-height and temperature probes in in-stream shallow wells to illustrate direction of flow (i.e., ground-water coming into stream or surface water losing to banks and bottom) across the Boise River near Parma, Idaho.



Used with permission and modified from
USGS graph of unpublished data from 2001.

to obtain the snapshot, a number of technicians must be on the reach at the same time and be making measurements at designated transects within a fairly short time period during stable flow. Water samples will be collected during the current-meter measurements and sent to the lab for major ion and trace-metal analyses. Discharge multiplied by salt concentrations will determine salinity loads in the stream. The seepage run is important to the study to determine areas of stream-water loss to the ground and to correlate this information with the types of soils and geomorphic structure of the channel.

5.4 Tracer Injection

Stream discharge can be calculated in gaining reaches by injecting a conservative salt (e.g., lithium bromide) at a known rate into the stream. The rate is mainly determined by the amount of salt needed to achieve the same concentration of salt throughout the reach being measured, which shows up as a plateau on a graph of concentration versus distance along the reach. The conservative salt mixes throughout the water column and also throughout the streambed alluvium. Tracer-injection methods can quantify gains but not losses of discharge; as once a tracer has mixed into the stream water, any loss of water (seepage out to the adjacent ground) does not change the concentration of tracer in the remaining water (Kimball and others, 1999). Gains (areas of ground-water inflow) cause a rapid dilution. The gaining areas of the reach show up as sharp downward curves that break up the established plateau on a graph. Water samples collected during the tracer to measure concentrations of the injectate are also utilized to measure concentrations of dissolved salts. Since the concentration of the injectate is used to determine discharge, once discharge is calculated it can be multiplied by each salt concentration to determine loads. The tracer injection method is important to the study to determine where along the reach salts are coming in, and to obtain the concentrations of salts and calculate loads. This information is analyzed with respect to the soils and ground-water chemistry in the piezometers in the gaining reach.

5.5 Soil Survey

An electromagnetic induction meter (EM38 and/or EM31) will be utilized to measure soil salinities and record areas of compositional (textural) change. The EM38 meter records apparent conductivity, which on the ground can translate into areas that contain higher or lesser amounts of salts and/or textural variability (e.g., sandy or clayey soils). A high water table can confound the meter; thus, care needs to be taken to do these measurements later in the summer when the water table drops. Studies have been done to compare different types of electromagnetic meters for different applications (e.g., Boettinger and others, 1997, and Dolittle and others, 2002). The EM38, which operates at a frequency of 13.2 kilohertz (kHz) (1 meter (m) intercoil spacing) and can measure to a depth of 0.75 m in the horizontal dipole orientation and 1.5 m in the vertical dipole orientation has been compared in the field with an EM31, which operates at 9.8 kHz (3.7 m intercoil spacing) and can measure to depths of 3 m in the horizontal dipole and 6 m in the vertical dipole orientation. The type of meter that should be used is mainly dependent on resolution required, depth required, and types of soil. Soil survey work is important to the study to establish soil salinities and textural variabilities in the ground in the gaining and losing reaches of the stream.

5.6 Weather Stations

Several weather stations are available in and near the study area. All of the stations have rain gages and some also measure wind direction, soil moisture, and air and soil temperature. Weather stations are important in order to record storm events, correlate data with the stream-flows, and to assess how precipitation affects salinity loads in the San Rafael River.

6.0 Analysis Techniques

6.1 Analysis Objective

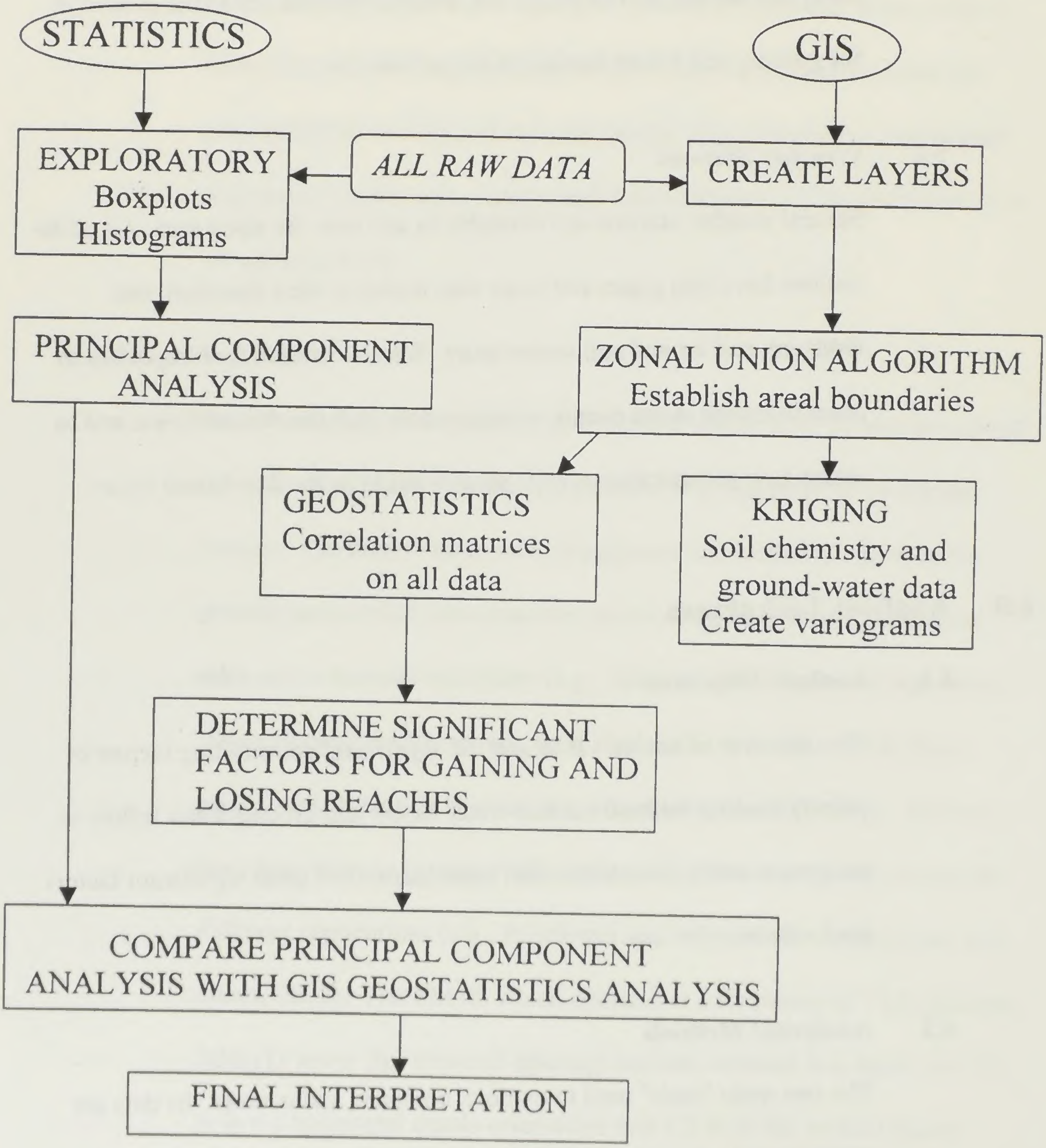
The objective of analysis is to sort out significant contributing factors of salinity loading for both surface-water runoff and ground-water inflow to the stream and to determine what combinations of these significant factors predominate.

6.2 Analytical Methods

The two main ‘tools’ used to explore, compare, and contrast the data are statistics and a geographic information system (reference figure 7 Analysis

FIGURE 7

ANALYSIS FLOWCHART


STATISTICS
GIS
EXPLORATORY
Boxplots
Histograms
ALL RAW DATA
CREATE LAYERS
PRINCIPAL COMPONENT ANALYSIS
ZONAL UNION ALGORITHM
Establish areal boundaries
GEOSTATISTICS
Correlation matrices on all data
KRIGING
Soil chemistry and ground-water data
Create variograms
DETERMINE SIGNIFICANT FACTORS FOR GAINING AND LOSING REACHES
COMPARE PRINCIPAL COMPONENT ANALYSIS WITH GIS GEOSTATISTICS ANALYSIS
FINAL INTERPRETATION

Flowchart). Statistical measures will be used on the numbers alone and will also be part of the GIS in a spatial analysis setting.

6.2.1 Statistics

Descriptive statistics will be used first on the data from field measurements. This entails utilizing exploratory analysis to investigate possible effects the measured values exhibit. Histograms and box plots will be generated to help determine the type of distribution (normal or non-normal). Principal component analysis (PCA) will also be run, which is a data-reduction method of separating groups of variables that correlate from other groups of correlating variables. PCA is a multivariate type of factor analysis that groups correlating variables to reduce the total number of variables – now called factors, i.e., variables that correlate are grouped and become, in a sense, a single factor. In theory, the resulting factors have very little or no correlation with each other. This reduces complexity and sometimes allows one to more easily detect structure in the relationships between measured variables (http://www.statsoft.com/textbook/stathome.html). For PCA, a covariance matrix (or correlation matrix if units are different) is constructed for all variables of interest. From this matrix a table is generated that lists the number of factor extractions based on descending amounts of correlation. In other words, correlations for different multiple variable combinations are computed giving regression lines that best fit the scatter plots of the data points. This process is called variance maximizing and it constructs factors (combinations of variables) that account for most of the variance in the data, then lists them in descending order such that each succeeding extracted factor accounts for less and less variability (Jackson, 1991). The real-world application of this type of analysis can be to identify the largest factor (combination of most important variables) and then succeeding factors (other possible combinations of variables that are not as important) in the study area related to salinity loading, i.e., what is the most significant combination of different types of data that accounts for salinity loading to the stream? (e.g., is soil texture (sand-loam-clay) combined with ground-water gradient the most important, or is soil salinity combined ground-water gradient more important?). PCA analysis results will be compared with GIS results, which is also a search for the most significant salinity-loading variables through spatial analysis and by utilizing the Geostatistics module of ArcGIS.

6.2.2 Geographical Information System Application

GIS analysis begins with development of an algorithm to utilize coverages (layers) of all collected data to spatially construct and compute zonal unions and derive comparisons of soil measurements, ground-water composition at different piezometer locations and adjacent stream-water compositions. Kriging will be part of the spatial analysis on the soil chemistry and ground-water data, but will be conducted as part of the geostatistics investigation (more information on kriging is given below).

GIS analysis helps to discern *how* data of different variables are grouping (e.g., zones of different soil textures with zones of ground-water chemistry) and *where* the data are grouping on the ground, i.e., spatial extents of different measurement variables (e.g., soil texture is one measurement variable and ground-water chemistry is another measurement variable). Then, one can examine the effects of the *how* and the *where* groupings with adjacent stream-water chemistry in gaining and losing reaches. Basically, this allows one to examine effects of different type soils along the stream. The ground-water chemistry is an intermediary tie to both the soils and the stream water. In summary, GIS spatial analysis will help determine areal size and spatial locations of highly saline areas and their effect on adjacent stream-water chemistry.

The geostatistics module is utilized for two main purposes: 1) developing correlation matrices, and 2) kriging analysis. Correlation matrices developed from the lay up of different measurement-variable coverages will help determine the significance of different combinations of the variables. Kriging analysis can help interpolate values in spaces between known ion-concentration/textural-composition data points for soil properties and for ground-water properties in areas between piezometers. Kriging is a minimum-mean-squared-error method of spatial prediction that gives observations closer to the prediction point more weight in the predictor (Cressie, 1991). The general kriging equation (ordinary kriging method) is essentially the same as the equation used for inverse-distance-weighted interpolation, but the difference is that rather than using the weights based on an arbitrary function of distance, the weights used in kriging are based on the model variogram. Construction of a variogram is the first step in the kriging process. A variogram consists of a plot of the calculated variance of each data point in a set with respect to each of the other points versus the distance between the points – this creates the experimental curve on the variogram. Once the experimental curve is computed, a model curve, which is a mathematical function that models the trend in the experimental curve, is then computed and plotted overtop of the experimental curve (http://www.ems-i.com/gmshelp/Interpolation/Interpolation_Schemes/Kriging). Ordinary kriging (described above) will be the basic kriging method employed. Universal kriging, which also takes nonstationary data into account and uses a “drift” polynomial function, may be used in areas of sloping surfaces. Zonal kriging, which allows one to define a set of zones with unique properties and their accompanying variograms, may also be employed. Though, zonal kriging can only be used on grid areas with uniform row and column widths.

7.0 Outline of Proposed Tasks

Table 1 lists the type and order of tasks to be conducted for this project.

TABLE 1. TASKS

San Rafael R. – Salinity source study **Principal Investigator: H. Hadley** **Bureau of Land Management, Utah** **U = Upper reach L= Lower reach** **DESCRIPTION:**	**Jan-Apr 03**	**May 03**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Jan 04**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep-Jun 05**
1. Develop/write project proposal	X																	
(Bur. of Land Management)																		
2. Write interagency contracts		X	X															
(Bur. of Land Management)																		
3. Install stream gaging stations (**U**, **L**)				X														
(U.S. Geological Survey)																		
4. Collect stage-height data (**U**, **L**)				X	X	X	X	X	X	X	X	X	X	X	X	X	X	
(U.S. Geological Survey)																		
5. Install piezometers (wells) (**U**)		X	X	X														
(Utah State Univ. and BLM)																		
6. Collect soil samples (**U**)		X	X	X														
(Utah State Univ. and BLM)																		
7. Collect well-water samples (**U**)			X											X				
(BLM)																		
8. Measure water levels in wells (**U**)		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
(BLM)																		
9. Conductivity probes (river, 1**U**, 1**L**)				X	X	X	X	X	X	X	X	X	X	X	X	X	X	
(BLM)																		
10. Seepage run/collect water samples							L							U				
(**L, U**) (USGS, Utah Water Lab)																		
11. Tracer injection/collect water samples (mid May) (**U**) (BLM)														U				
12. Soil survey (**U**, **L**)			X											X				
(USDA Soil Survey Lab)																		
13. Spatial analysis – GIS/statistics															X	X	X	X
(BLM)																		
14. Progress reports (J = Jan 2005)					X					X							X	J
(BLM)																		
15. Draft of Final Report (J = June 05)																		J

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APPENDIX A

Literature Review: Selected written summaries

APPENDIX A – Literature Review: Selected written summaries

Butler, D.L., and Leib, K.J., 2002, Characterization of selenium in the lower Gunnison River Basin, Colorado, 1988-2002: U.S. Geological Survey Water-Resources Investigations Report 02-4151, 26 p.

REVIEW

Butler, recently retired, has written a number reports on salinity on the Colorado Plateau and is considered an expert in salinity science. He has done a number of characterization and trend analysis studies for the Grand Valley (Gunnison River) near his home in western Colorado. Selenium, which is ubiquitous in the Mancos shale, often becomes concentrated in irrigation return-flow waters or as just naturally loading ground-water inflow in tributaries of the Gunnison River. Selenium can have adverse effects on water quality, fish and wildlife. The objectives of this report were to characterize selenium concentrations and loads in tributary streams of the North Fork of the Gunnison and tributaries of the Gunnison River downstream from the Smith Fork to Whitewater. Also, Cedar Creek and Loutzenhizer Arroyo in the nearby area were studied for concentrations and loads.

RESULTS

This project is part of ongoing studies of the National Irrigation Water Quality Program (NIWQP). During 1999 and 2000, North Fork of the Gunnison River accounted for about 7 percent of the selenium load in the Gunnison River at Whitewater. The Uncompahgre River, which flows into the Gunnison River in the town of Delta, accounted for about 38% of the selenium load over the period 1988-2000 and is the largest 'loader' in the region. Selenium from Montrose Arroyo accounted for the largest load (about 32%) into Cedar Creek, which flows into the Uncompahgre. Loutzenhizer Arroyo, which feeds into the Uncompahgre River near the town of Olathe is suspected as being a major source of selenium loading too, but due to various problems with a tracer study in February 2000, loading numbers could not be calculated.

DIFFERENCES IN TERMS OF MY STUDY

1. Objective: Butler and Leib investigated selenium loading in western Colorado in tributaries that flow into the Gunnison River. My study will assess selenium concentrations in the soil, ground and surface waters in the San Rafael River, but my focus it to create a methodology that identifies the major transit mode of salt loading in a watershed.
2. GIS analysis: In terms of what Butler and Leib were investigating, GIS mapping and analysis would have added a complimentary "view". However, even though they mentioned the rock, soils, and land use of the area, they primarily focused on water quality in streams and rivers and as such, GIS analysis was not as important to their study as it will be to mine.

Branson, F.A., and Owen, J.B., 1970, Plant cover, runoff, and sediment yield relationships on Mancos shale in western Colorado: Water Resources Research, v. 6, n. 3, pp. 783-790.

REVIEW

Correlation analysis was conducted to discern degrees of relationship between amount and type of vegetation growing in an area, and hydrologic runoff events and sediment yield in seventeen watersheds in western Colorado (Badger Wash basin near Grand Junction). Often, it is difficult to determine runoff and sediment yield in ungaged watersheds on the Plateau. There is also often a lack of data available for kinds and quantities of vegetation, surficial geology, soils, and watershed morphology (This was 1970, since then more data are available, but it seems like basic data are still lacking) in ungaged drainages. Vegetation in these watersheds is tied to different types of soils developed from several types of geologic formations. Shadscale (Atriplex confertifolia) and galleta grass (Hilaria jamesii) grow on sandy soils and Nuttall saltbush (Atriplex nuttallii) grows sparsely on clayey soils. Annual precipitation is about 8.5 inches. Runoff and sediment yields were measured volumetrically in small reservoirs at the end of each of the 17 watersheds. Specifically, staff gages or water-stage recorders measured runoff to the reservoirs and sediment yield was determined by successive topographic surveys of the reservoirs.

RESULTS

Highly significant correlation coefficients (0.73 to 0.91) were found for percent bare soil and runoff. Less significant or not statistically significant were the relationships between bare soil and sediment yields. Geomorphic parameters such as slope and relief ratio were more highly correlated with sediment yields than with runoff. There was also a varying seasonal statistical significance: correlation coefficients for spring runoff and vegetation measurements were higher than autumn. It was surmised that the spring correlation was higher due to livestock trampling causing more bare soil and/or their grazing of the vegetation on winter allotments prior to spring growth occurring.

DIFFERENCES IN TERMS OF MY STUDY

1. *Objective:* Branson and Owen's study focused on correlation analysis to determine what affinities the different variables have for each other when assessing runoff and sediment yield. My study also utilizes multivariate correlation analysis, but not to investigate runoff and sediment yield. I utilize correlation analysis to ascertain the major travel mode of salt to the stream (surface-water runoff or ground-water inflow).
2. *Absence of GIS analysis:* 1970 was too early for GIS technology. This study would be interesting to redo with the aid of GIS mapping and analysis.

Chadwick, D.G. Jr., 1978, Hydrosalinity modeling in the Price River basin: M.S. thesis, College of Engineering, Utah State University, Logan, Utah, 96 p.

REVIEW

He assesses the division of salinity sources (ag vs. natural), notes the percentage disparities between different studies (Hyatt, 1970 – no reference!, and Gifford et al., 1975) and states the following objectives for his study:

1. To propose and test mathematical relationships by which estimates of salt contributions of overland flow and micro-channel processes can be obtained.
2. To incorporate the relationships developed under objective 1 into a digital computer model.
3. To complete a hydrosalinity simulation of the Price R. Basin.
4. To provide estimates of relative importance of some salinity sources using the results of the model studies.

RESULTS

In the Price R. Basin, model results indicate that agriculture is the predominate cause of salt production and mobilization. An interesting point is that he accounts for salt production for evaporation processes and deduces that the "great majority" of "evaporation is a result of consumptive use of water by agricultural crops."

DIFFERENCES IN TERMS OF MY STUDY

1. *Salt source division:* His division for salt sources is agriculture vs. natural, whereas my division is transit mode: surface runoff vs. ground-water inflow processes.
2. *Approach:* He develops a mathematical model to determine salt sources. I am developing a methodology to determine salt sources. My methodology is made up of different types of scientific measures. His model is based on a numerical algorithm.
3. *Responsible factors:* He has to arbitrarily decide (make assumptions) which are the necessary factors for his model. I will collect soil and water data, enter them into a GIS, and utilize statistics to determine significance of many possibly-related factors (pair-wise correlations). The significance of factors determines which ones are necessary for the study site and could be used in a future model (I do not address the modeling step, which would be next).
4. *Method:* He uses a model comprised of a mathematical algorithm. I will use a method comprised of 2 parts: basic scientific measures and GIS processing.

Deyo, A.E., 1984, Salinity investigations of Mancos landforms and springs in the upper Colorado River basin: Ph.D. dissertation, University of California, Davis, CA, 184 p.

REVIEW

Deyo's objective was to "assess the contribution of dissolved mineral salts to the Colorado R. by natural forces acting within a small watershed in Western Colorado." Additionly he was interested in identifying "correlative parameters" that might be utilized to predict salt-loading potential of other, similar areas. Parameters considered included: climate, geologic parent material, soils, geomorphic units, salt contents and salt mineral species. His study area was West Salt Creek that flows into the Colorado R. near Grand Junction, Colorado. The way in which he went about it was to: "1) delineate major soil types, geomorphic units and geologic strata within the non-agricultural portion of the" area at a finer resolution than was available; "2) identify salt-producing evaporite and precipitate mineral species in the different soils and formations; 3) assess the relative magnitude of salt loading by means of surface runoff, erosion cutting and seep discharge" in the area; and "4) identify parameters that may be utilized for prediction of salt-loading potential of other similar natural areas." Deyo's last chapter is another objective that involves proposing salinity-control measures for small watersheds.

RESULTS

Deyo's salinity study is comprised of geomorphic and hydrologic investigations. It focuses well on determining 10 major types of geomorphic forms (features) and the soil properties (electrical conductivity) that are typical of these different forms. He has compartmentalized his study into characterization/investigation of geomorphology and hydrology in the watershed, but doesn't substantially attempt to integrate the two components in order to determine/quantify critical salinity areas (e.g., water analysis tied to adjacent soil salinities). In his characterization/measurements, he has discovered many important factors of salinity contribution for both geomorphic features and river reaches. There is a summary section at the end of each chapter characterization, but not an overall discussion/integration summary at the very end for all the data. There is a 'tying-together'of knowledge gained from each of the chapters in the last chapter in order to discuss salinity-control measures. But this is a discussion of construction/mitigation plans and not an interpretation of all of the data together. It is obvious that Deyo's investigation and gained knowledge gives him good insights in the last chapter that deals with proposing salinity-control measures.

DIFFERENCES IN TERMS OF MY STUDY

1. *Salt-loading potential:* Deyo assesses salt-loading potential mainly through description of the types of salts (e.g., gypsum, epsomite, kieserite, mirabolite, thenardite, etc.), their associated rock formations, and typical geomorphic and hydrologic locations and modes of loading (e.g., seeps, springs, discussion of diurnal and seasonal variations). My study will attempt to quantify loading potential through areal GIS analysis of several layers, e.g.: 1) drainage boundary, 2) areal map of soil salinity concentrations from EM38 data, 3) ground-water chemistry from the piezometer field, 4) adjacent stream-salinity concentrations along the reach, and 5) a map created from tracer injection that shows probable areas of ground-water inflow along the reach. The spatial measurement level from the lay-up of these coverages will result in an ordinal scale at the least (high,

medium, low potential) and possibly an interval scale based on contour intervals of the soil-salinity and ground-water constituent concentrations.

2. *Absence of GIS analysis:* The major difference, as with all other studies, is that no GIS analysis of the data was done. If GIS analysis had been developed as far as it is today, this would have been an excellent study to apply it to.
3. *Emphasis of measurable factors:* My study will include a geomorphic component, but it is not as major a component as in Deyo's study. This is because his objectives were basically different from mine. He wanted to know how geomorphic features were associated with salinity, whereas I want to discern what factors, of which geomorphic features are one factor, decide the transit mode of salt loading to the stream.

Duffy, C.J., Jurinak, J.J., Sangani, S., and Azimi A., 1985, Identification and modeling the impact of marine shale bedrock on groundwater and stream salinity: Upper Colorado River Basin: Utah Water Research Laboratory, Hydraulics and hydrology series UWRL/H-85/01, Utah State University, Logan, Utah, 104 p.

REVIEW

The objective of this study was to investigate the physical and chemical factors that control the interactions between ground water and marine shales of the Price River basin. As such, it is primarily a chemistry investigation. However, another study by CH2M Hill was included to bring in additional information on ground-water flow paths, salt transport and weathering processes that affect salt loading. USGS geochemical models PHREEQE (equilibrium) and BALANCE (geochemical evolution) were used on the ground-water data. With knowledge from these two models a third model was built that was a saturated-unsaturated 2-dimensional flow model (UNSAT) and used along a ground-water flow path. UNSAT is a solute transport model that examines the relative importance of advective, dispersive and diffusive mixing processes along the flow path. The results from this study were utilized to assess management methods that might be most effective, such as, improved irrigation efficiency, canal lining, and retiring irrigated land. Duffy et al. state that: "… salinity-control projects must be based on quantitative relationships estimating salt-loading rates as a function of controllable parameters in areas targeted for control measures."

RESULTS

CH2M Hill's study postulates that as much as 90 % of the stream salinity originates in ground water flowing through salt-bearing strata. Utah Water Research Laboratory work also found that only a small amount of the salt loading was coming from the land surface and stream channels (Riley and others, 1982, and Bowles and others, 1982). Thus, the emphasis is on ground-water movement and how the water quality changes in this type of environment. Many excellent chemical fate and transport processes were revealed by this investigation, allowing one to understand on a micro-scale how water quality changes as it moves along a ground-water flow path. Gypsum dissolution and Na-Ca exchange were found to be the most predominant reactions occurring in the ground-water system. The major ground-water transport process for the Mancos shale environment appears to be a slow vertically upwards release of sulfate salts via diffusion.

DIFFERENCES IN TERMS OF MY STUDY

1. *Land use:* This study looks mainly at an irrigated environment. My study looks at public land that is grazed, though irrigation exists up-gradient. The water amount for an irrigated environment is higher than for the natural environment in this basin and the timing of when the ground receives water is also different (regular growing season vs. monsoonal events on public lands)
2. *Primary focus:* This study investigates the chemical processes: fate and transport of salts. Whereas, my study, while chemistry oriented (water and soil), investigates the possible correlative effects of other processes too, such as, precipitation, physical watershed structure (gaining/losing reaches and geomorphology) to determine transit mode of salt loading.
3. *Method:* This study uses geochemical modeling to look at fate and transport of the chemical salt elements. My study will use GIS analysis to combine/correlate/interpolate not only chemical data, but structural data also.

Gellis, A., Hereford, R., Schumm, S.A. and Hayes, B.R., 1991, Channel evolution and hydrologic variations in the Colorado River Basin: factors influencing sediment and salt loads: Journal of Hydrology, v. 124, pp. 317-344.

REVIEW

Before Hayes produced his Ph.D. dissertation (see below) he worked with the above authors in investigating small-scale (large area) controls on sediment and salt loading in the Colorado River Basin. Gellis' paper discusses the evolution of landforms with time and their response to climatic change over the last approximately 140 years. Dates vary regionally, but some studies have evidence of deeply incised arroyos going back to 1865, and in other areas there is evidence from the 1910s. Since the 1940s, Gellis has tracked a decline in suspended-sediment and salt loads, but not necessarily a decline in discharge in the major tributaries of the Colorado River.

RESULTS

The channel evolution pattern that emerges begins with initial high erosion rates as steep banks slough down and create large amounts of sediment and salt loads in the channels. Water moving between the steep banks exacerbates the erosion process and loads are carried down stream. As time goes on, the channels widen and sediment loads from erosion, though still occurring, have a tendency to spread out on the new emerging floodplain and remain to a great extent in place. Water moving over the sediments is now spread out over a larger surface and while it does carry a load, the movement force of the water over the larger area is lessened by dispersion. On the emerging floodplain, vegetation has a better chance of establishing itself and it will also aid in lessening the load transmittal.

DIFFERENCES IN TERMS OF MY STUDY

1. *Scale:* Gellis is concerned with understanding movement of sediment and salt loads in large regional areas that include numerous watersheds that feed the Colorado River. His approach investigates and seeks to 'tie in' the evolutionary loading pattern over the last 100+ years to climatic history and geomorphic processes. My scale is smaller and is concerned with not only overland movement of sediment/salt loads, but also with movement of ground-water salt loads, where climate is an important factor, but other factors create effects as one takes a closer-up view, e.g., soil textures and soil and water chemistry play a large part in discerning overland loading versus ground-water loading into stream channels.
2. *Measurable factors:* Again, with Gellis' regional outlook, climate and geomorphic processes predominate. With my study, climate and geomorphology are only 2 factors and are joined with soil textures and soil and water chemistry to identify loading.
3. *Absence of GIS analysis:* It would be interesting to reproduce this study and use GIS analysis to see if it would produce a similar conclusion.

Hayes, B.R., 1995, Geomorphic and climatic controls on streamflow, sediment, and salt loads, upper Colorado River Basin: Ph.D. dissertation, Department of Earth Resources. Colorado State University, Fort Collins, CO, 184 p.

REVIEW

Hayes investigated whether there was a *major* trend in the dissolved-solids loads (dsl) of streams within the upper Colorado River Basin by analyzing the relationships of dissolved-solids loads with regional climatic and geomorphic processes. Specifically, he studied: 1) historical gaging records of streamflow and dsl of the major rivers in the Basin; 2) conducted reconnaissance alluvium sampling to determine soluble salts that were stored in the alluvium and channel sediments; 3) relation between regional precipitation and annual streamflow to see how they were related to large-scale atmospheric circulation patterns; and, 4) relation of climatic and geomorphic controls on the long-term variations in sediment and salt yields.

RESULTS

Hayes presents evidence that since the early 1940s, sediment yields Basinwide have declined. When the channels were initially forming there was high erosion, but with time the channels widened and began storing (aggrading) sediments, which reduced sediment loads within the Basin. While suspended-sediment and dissolved-solids discharge has been decreasing, streamflow has not significantly changed. Prior to 1940s there was a larger sediment yield caused by widespread arroyo incision. At the time of his study (1990s) he found significant amounts of sediment and salt were being stored in the lower and middle reaches of ephemeral streams as the channels evolved toward relative stability. Long-term records were used from gaging stations that had no, or little, regulation or diversions. With the exception of small impoundments, he was able to obtain data from tributaries that were generally free-flowing and unregulated prior to 1964. Hayes investigates the correlative effects between 2 major climatic indices, Central North Pacific (CNP) and Southern Oscillation Index (SOI), and streamflows/dsl. In the northern part of the Colorado River Basin, he finds a strong correlation in winter between the CNP and streamflow. By contrast, he finds that the in northern Arizona, northwestern New Mexico, and SW Colorado there is a negative correlation between the SOI and streamflow, i.e., in strong El Nino years, the streams may flow heavier. Hayes did not find any significant correlation between discharge and dsl with either index for east-central Utah and west-central Colorado; suggesting that topographic controls may complicate the climatic circulation patterns in this central area.

DIFFERENCES IN TERMS OF MY STUDY

1. *Overall goal:* Hayes is investigating whether sediment loads have decreased or increased and why. Whereas I would like to investigate what major measurable factors in a watershed determine the type of travel for salt loads.
2. *Emphasis of measurable factors:* SCALE - In order to determine delivery potential, Hayes looks at mainly long-term streamflow and dissolved-solids loads records of several large rivers in the Basin, their morphologic stream-channel evolution, and regional climate records. Thus, his is a large picture. Mine is a smaller individual watershed picture, but a standard methodology is applied to that smaller area that includes an emphasis on streamflow, dsl, pin-pointing gaining/losing areas of reaches, shorter-term climate records (probably 3-4 decades compared to Hayes' approximately 7-10 decades), soil and water chemistry, soil textures (runoff capability), and local watershed geomorphology.
3. *Absence of GIS analysis*: Again, as in all the other salinity studies reviewed, GIS analysis has yet to be employed. But unlike the other older studies, this one was conducted during the first half of the 1990s when GIS was being used more regularly in other non-salinity work.

Jackson, W.L., and Julander, R.P., 1982, Runoff and water quality from three soil landform units on Mancos shale: Water Resources Bulletin, American Water Resources Association, v. 18, no. 6, pp. 995-1001.

REVIEW

Simulated rainfall plots were used to investigate relative yields of water, sediment, and salt on three soil landform units of the Mancos shale in the Price River Basin, Utah. The three soils were: residual shale-derived soils in a low-relief area, recent alluvial deposits that exhibited a cracked structure, and a largely dissected Mancos shale soil on steep inclines. As such, this study deals mainly with the surface-runoff process. It has been deduced that runoff in the Colorado River Basin mainly occurs during high intensity, short duration summer convectional storms. For the second type of soil, the recent-alluvial deposit, subsurface flow was also measured, by constructing an angle-iron trough installed at the bottom of the slope beneath the soil contact. Creep meters (0.3m x 0.3m wooden frames with spikes protruding approximately 6 cm into the soil) were also installed to measure the movement of soil on the surface, one of which was connected to a Stevens recorder to measure rate of soil creep over time for the duration of the simulated rain event. The primary objective was to determine average yields of sediment from dissected Mancos shale uplands. This study is related to a question of the efficacy of gully plugs that the BLM uses throughout the Colorado River basin to reduce sediment transport.

RESULTS

The third type of soil environment, dissected Mancos shale soil on steep inclines produced the highest sediment and salinity loads. The 1st type, Mancos shale-derived soils in a low-relief area was the second highest producer. The 3rd type of soil, recent-alluvial deposits did not exhibit any substantial yields because the water infiltrated down through cracks in the alluvium. Rilling accounted for about 80% of the runoff yield in the 3rd type of soil landform. The authors stated that, "carefully designed and located basin plugs can be used effectively to trap sediment, water and salt from dissected shale uplands."

DIFFERENCES IN TERMS OF MY STUDY

1. *Objective:* Jackson mainly studies the surface runoff process, seeking to better understand how runoff occurs on several different types of soil landforms. My study seeks to identify whether you will have a surface runoff process or ground-water inflow process occurring in an area by analyzing a number of different factors (e.g., soil texture, soil and water chemistry, geomorphology, climate, etc.) and ascertaining their significance singularly or combined.
2. *Importance of GIS analysis:* Even though GIS analysis could be done for this study, it is probably not as useful as it will be for my study.

King, N.J., and Mace, M.M., 1953, Sedimentation in small reservoirs on the San Rafael Swell, Utah: U.S. Geological Survey, Circular 256, 21 p.

REVIEW

This is one of the few studies that were done in the San Rafael River drainage. It is included here because of that fact, even though it is an older study. King investigated the rate of sedimentation utilizing small reservoirs within the watershed. He states, "Measurement of sedimentation rates in small reservoirs offers the only feasible source for data of this type. As streams tributary to the reservoirs are strictly ephemeral, flow occurs at unpredictable periods and only in direct response to precipitation. Direct sampling of streamflow is thus impractical because of the great expense involved." This is still true to a great extent today, as small reservoirs are often used to study sediment runoff. The rate of sediment production is dependent on the occurrence and amount of precipitation. King characterized the type of erosion (gullying and sheet) for soils from the various types of underlying geologic formations.

RESULTS

King's study confirmed many of the basic assumptions we start with today. "Movement of sediment from upland areas and eventually into main drainages and rivers is by no means through continuous transportation of material…." "Instead it consists of a series of intermittent erosional and depositional phases that present a pulsating movement." There are periods of time when even though erosion is occurring, relatively small amounts of sediment may be transported to perennial streams – instead the erosional material remains in the ephemeral or intermittent drainages until another period of rapid movement occurs and there is substantial removal of the built-up erosional material from the basin. One interesting finding was that erosion in the San Rafael River drainage (at least up until 1953) "has kept pace with or exceeded the rate of soil development such that existing thin soils or weathered mantles are very closely related to the parent rock." This, of course, does not hold for alluvial fill in stream channels. Another important basic observation is that dry years tend to denude areas of vegetative cover and thereby lower the area's resistance to erosion. So, episodic rainfall events following long dry periods can possibly cause some of the highest sediment runoff.

DIFFERENCES IN TERMS OF MY STUDY

1. *Objective:* King studied the phenomenon of surface-water runoff and it's relation to sedimentation rates. My objective is to discern whether a surface-water runoff process is likely to occur in an area, or if the main transit mode is ground-water inflow to the stream. So, I am attempting to discern what type of transit mode is occurring and I am not studying rates.
2. *Method:* To a great extent, King utilizes physical structures as his measurement guide. Whereas, I rely more on chemical measurements (including conductivity) to guide my investigation.
3. *Absence of GIS:* GIS was not in existence back in the early 1950s, so it was not possible to analyze the data in this manner. This would be an interesting study to redo with the aid of GIS analysis and mapping.

Laronne, J.B., 1977, Dissolution potential of surficial Mancos shale and alluvium: Ph.D. dissertation, Colorado State University, Fort Collins, Colorado, 128 p.

REVIEW

There were 2 main objectives for Laronne's study: 1) Determination of the amounts of salt (soluble mineral content, storage in alluvium, and in associated Mancos shale bedrock) in order to determine salinity potential of such deposits; and 2) Evaluation of the relationship between salt release and the erosion of valley alluvium. The hypothesis here was that salt is stored in alluvium and released after alluvium is eroded. For the second objective, comparisons were conducted of morphological differences between basins of high and low salt release.

RESULTS

Rates of dissolution for soluble salts of the Mancos shale and alluvium varies substantially. As sediment concentration increases in water, so does the time it takes for partial chemical equilibrium to occur for the sediment:water mixture. Depending on the sediment concentration, the time interval for partial chemical equilibrium can be from a few minutes to several days. This means that in rivers with high-suspended sediment, there is a non-equilibrium state. Also, from this deduction, it follows that the yield of dissolved solids in a river should actually be greater than the yields calculated from electrical conductivity (EC) measurements or water sample analysis. Chemical analysis does not take into account the dilution effect (which might increase the dissolved yield by as much as 500 percent) while EC measurements fail to account for whether or not the runoff is kinetically equilibrated with the transported sediment. For the second objective, evaluation of the relationship between salt release and the erosion of valley alluvium, Laronne found that areas underlain by Mancos shale and its associated alluvial materials are presently major diffuse sources of salts and that they contribute significant amounts of sediments and salts, especially when gullied.

DIFFERENCES IN TERMS OF MY STUDY

1. *Objectives:* Laronne's study focused mainly on chemistry to determine salinity potential in a watershed. Erosion was the physical parameter he investigated along with chemical aspects of Mancos shale constituents. For my study, salinity potential (mainly through constituent characterization) is one factor, which is investigated along with areal contribution and types of soil texture (affects movement) throughout the watershed to discern mode of transit (overland runoff or ground-water inflow to streams).
2. *Absence of GIS analysis:* As with all the other salinity studies reviewed, this study did not employ GIS analysis – as it was conducted prior to GIS technology being fully developed and marketed.

Lin, A., 1984, A study of salinity production from wildlands of Price River basin, Utah: *In* French, R.H., (ed.) Salinity in watercourses and reservoirs, Proceedings of the 1983 International Symposium on State-of-the-Art Control of Salinity, July 13-15, Salt Lake City, Utah, Butterworth Publishers, Stoneham, MA, pp. 417-426.

REVIEW

Field data were collected in autumn 1981 on 19 rainfall events in four watersheds: 1) Wattis – ephemeral stream on Mancos shale, 2) Soldier Creek tributary – ephemeral stream on Mancos shale, 3) Coal Cr. tributary – ephemeral in moderately saline soils, and 4) Grassy Trail Cr. – intermittent stream draining many different soils. ISCO auto-samplers were used to collect the samples.

RESULTS

The major soluble mineral is gypsum from the Mancos shale. Various other types of sulfate minerals have also been dissolved. Mean soluble content of Mancos shale is about 2%, with a variance for 1.5% for the upper Bluegate to 6.3% for the Mancos undivided. As sediment concentrations increase in overland flow, solutes concentrations rise also. Steep slopes will also raise the solute concentrations. Channels through exposed Mancos shale or with thin alluvium on top of Mancos are salinity hazard areas. Soil crusts of efflorescence salt are a large part of the contributing source during runoff. There is a large variance of storm-related salt load from wildlands: 1% to 50%. Hillslope erosion is a major player and it is important to distinguish 'first event' (after a long dry period) from successive events, as the first event generates higher loads.

DIFFERENCES IN TERMS OF MY STUDY

1. *Objective:* The objective was to study overland flow from storm events to determine: 1) the amount of salt, 2) types of salt, and 3) important contributing geomorphic forms in Mancos environments. My objective is to distinguish between 2 types of transit sources in a watershed: 1) overland flow to the river, and 2) ground-water inflow to the river.
2. *Absence of GIS analysis:* Again, this study, carried out in the early 1980s, does not utilize GIS analysis.

Lusby, G.C., 1970, Hydrologic and biotic effects of grazing vs. nongrazing near Grand Junction, Colorado: Journal of Range Management, v. 23, n. 4, pp. 256-260.

REVIEW

From the 1950s through the 1970s a study was carried out on designated plots in Badger Wash, Colorado. The USGS was in charge, but a number of other agencies participated. The purpose of the study was to look at the effect of grazed and nongrazed areas. Measurements of precipitation, runoff, erosion, and vegetation have been collected in four pairs of watersheds, of which one plot in each pair has been grazed and the paired plot has not been grazed since the beginning of the study – mid 1950s.

RESULTS

In all four grazed areas, there has been a slight increase in the amount of bare soil (decrease in plant cover), whereas the plant cover on the nongrazed plots remained unchanged. Runoff in the nongrazed plots is about 30% less and sediment yield is about 45% less. The greatest change in measurements occurred after 3 years into the study. It appears that there is a strong relationship between amount of bare soil and runoff production.

DIFFERENCES IN TERMS OF MY STUDY

1. *Objective:* Lusby investigated the phenomenon of runoff as it pertained to grazing. So, he was interested to determine what factors (such as the amount of

bare soil) were the most important contributors to increased runoff. I am not trying to measure differences in runoff in my study, but attempting to discern if we are in an area that will have runoff – what factors determine that?

2. *Absence of GIS analysis:* Again, because it is an older study, GIS was not developed yet.

Malekuti, A.A., 1975, Salt leaching from plants as one source of diffuse salt movement from rangelands, M.S. thesis in Range Science, Utah State University, Logan, Utah, 107 p.

REVIEW

This study investigated the importance of salt released in water dripping from plants and the salt movement and contributions due to plant litter on the ground. Different plant species were evaluated to discern which ones were major salt contributors. This experiment utilized simulated rainfall of different intensities and duration. Foliage leaching was also conducted in the field on different plant species. Collected water samples were analyzed for: sodium, potassium, calcium, magnesium, cloride, bicarbonate, carbonate, and sulfate.

RESULTS

Light intensity rain of long duration is slightly more efficient in salt removal from plants and their residuals than is heavy rain of shorter duration. Atriplex species, greasewood, halogeton, and salt cedar contributed the most salt, whereas pinyon pine and juniper contributed the least salt.

DIFFERENCES IN TERMS OF MY STUDY

1. *Focus*: Plants were the focus here – what types of plants and their associated litter are major contributors of salt production. In terms of the Colorado Plateau, where average annual precipitation in many of the tributaries that feed the Colorado River is at best 6-8 inches, there just is not much plant growth – there are large areas of bare soil. So to do a study on vegetative matter's influence on salt loading becomes a minor player in the bigger picture. My study does take plants into account, mainly for the water budget of the watershed, as each species has a basic water coefficient determined for evapotranspiration, which can be multiplied by areal growth of that species. However, in terms of determining what type of transit process is predominating: overland runoff versus ground-water inflow to the streams, plants are not a big player. The part they do play in the riparian areas is that if an overland flow process predominates, then the plants may and usually do retard movement towards the stream. Their root systems may also retard ground-water inflow into the streams.
2. *Absence of GIS analysis*: This study is also too old to have benefited from GIS analysis, but it could be redone today and interesting findings gleaned from areal analysis of different types of plant cover.

Miller, W.R., 2002, Influence of rock composition on the geochemistry of stream and spring waters from mountainous watersheds in the Gunnison, Uncompahgre, and Grand Mesa National Forests, Colorado: U.S. Geological Survey Professional Paper 1667, 52 p.

REVIEW

This was an interesting paper, because instead of the usual 'on-the-Plateau' studies, this study focused on the headwaters, in the mountains, before the rivers travel down lower to the Plateau, picking up salt as they go. Thus, it provided a geochemical baseline for rivers and springs that come out of the western Colorado mountains. Miller studied waters that underlain by 10 different rock composition types in the Gunnison, Uncompahgre, and Grand Mesa National Forests (GMUG). Water samples were collected in mountainous terrain that has much less evapotranspiration, higher amounts of precipitation, and lacks extensive ground-water aquifers. These waters react quickly to changes in input of water from rain and melting snow and can be vulnerable to anthropogenic impact.

RESULTS

Miller found that waters carrying the highest load of total dissolved solids came from mountainous watersheds that were underlain by Paleozoic sedimentary rocks (Mancos shale is younger Mesozoic sedimentary rock). The main salt mineral was gypsum, as it also is in the Mancos shale. Water that has the next highest total dissolved solids came from mountainous terrain that was underlain by Mancos shale. This study points out the importance of rock composition in the headwaters when determining types of water and when comparing the headwater geochemistry to the river's geochemistry as it moves out onto the Plateau.

DIFFERENCES IN TERMS OF MY STUDY

1. *Objective:* This study is fairly unique, as most of the salinity studies are done on the Plateau. Miller went up into the headwater regions and water-quality sampled to better understand and characterize how the rock types influenced the hydrogeochemistry of the river waters. So his is a study that ties the rock to the water and sees how the rock influences the chemistry of the rivers. My study also does this, but is focused on how the rock and soil affect the travel of the water, and hence salt-loading to the river.
2. *GIS analysis:* Most likely (not specifically stated), Miller used GIS to create his maps, but did not utilize the analysis capability of GIS. He did descriptive statistics on the water sample data to determine ranges and means. He also utilized PHREEQC (geochemistry model) to gain an understanding of processes such as chemical speciation of elements and the identification of the saturation state of minerals that possibly control the concentration, mobility, and attenuation of elements in the stream water. I will utilize GIS for both mapping and analysis of my soil and water data.

Mueller, D.K., and Moody, C.D., 1984, Historical trends in concentration and load of major ions in the Colorado River system: *In* French, R.H. (ed.), Salinity in watercourses and reservoirs, Proceedings of the 1983 International Symposium on State-of-the-Art Control of Salinity, July 13-15, Salt Lake City, Utah, Butterworth Publishers, Stoneham, MA, pp. 181-192.

REVIEW

This paper provides a good overview of the salinity situation in the Colorado River Basin. It is a compilation and analysis of the historical data. Gives the reader information on historical congressional acts and how they came into being. For example: In 1972, water quality was covered by the Federal Water Pollution Control Act. The standard for total dissolved solids (TDS) concentration was set to the average at that time, thus establishing a policy of non-degradation. Soon after the Federal Water Pollution Control Act came the Colorado River Basin Salinity Control Act of 1974, which authorized 4 salinity control projects for construction and 12 other projects for investigation. Early on all predictions showed increases in TDS, but from 1970 to 1980 there was actually a decrease. At the time the paper was written, it was not clear whether the decrease was part of long-term cycle or was indicative of a permanent change in the system.

RESULTS

Six solutes were selected for analysis: calcium, magnesium, sodium, chloride, sulfate, and bicarbonate, which made up more than 95% of the TDS load. Mean daily streamflow, daily specific conductance, and periodic chemical analysis were the main data retrieved from USGS' WATSTORE data base. Reservoirs can stabilize the flow and trap sediment behind their dams – statistically producing few significant trends. Trends were in evidence on unregulated portions of the river. Significant mean value differences were easier to identify than trends. Trends are easier to see during low flow periods. Mueller and Moody also found that no single dependent variable is clearly preferable for identification of changes or trends.

DIFFERENCES IN TERMS OF MY STUDY

1. *Objective*: Mueller and Moody's focus was to look at long-term chemical and discharge data on major tributaries and main stem Colorado River to see if trends existed and to see if any one particular variable could account for the trend. So one difference between their study and my study is scale – their study covered the Colorado River Basin, whereas mine is done in a single watershed, but could be used in other watersheds – one at the time most likely. Another difference is that they were searching for concentration and load trends, whereas I am attempting to come up with a methodology that determines the major transit mode of the salt loads.
2. *Absence of GIS analysis*: Muller and Moody used statistical analysis, but not in a geographic information system.

Mueller, D.K., and Osen, L.L., 1988, Estimation of Natural Dissolved-Solids Discharge in the Upper Colorado River Basin, Western United States: U.S. Geological Survey Water-Resources Investigations Report 87-4069, 62 p.

REVIEW

The objective was to estimate monthly natural dissolved-solids discharge at selected sites in the Upper Colorado River Basin based on measured flows. A statistical weighted least-squares regression was conducted on the data from a calibration site. The model gives natural dissolved-solids discharge as the rate of inorganic-solute flow past a specific site that would have occurred if there had been no water-resources development in the basin upstream from the site. Of course, there has been water-resources development in the basin, so after calibration, which took these development factors into account, the development variables in the model were assigned a value of zero to yield a relation between dissolved-solids discharge and streamflow for conditions of no upstream development. This work is tied to a Bureau of Reclamation (BOR) comprehensive river-basin model (Colorado River Simulation System – CRSS) for studying the operation of reservoirs on the Colorado River System. A dissolved-solids routing module was incorporated, which goes through a monthly time-step using the hydrologic record from 1906 through 1983 adjusted to natural condition. Specifically, mass-balance estimates of dissolved-solids discharge are computed by subtracting the dissolved-solids discharge diverted (from water-development projects) and adding the discharge contributed by water-development projects to the discharge that would have been present under natural conditions. Hence, one has to have already calculated estimates of natural dissolved-solids discharge for all selected river reaches used in the model.

RESULTS

The outcome from Mueller and Osen's work was estimates of monthly natural dissolved-solids discharge for 16 sites in the Upper Colorado River Basin that the BOR can use in their CRSS model. Limitations of Mueller and Osen's modeling work includes a lack of data with which they could adequately represent all the effects of development and verify the estimates of monthly natural dissolved-solids discharge. However, good correlation coefficients for the relation of dissolved-solids discharge estimates derived and historical data were obtained.

DIFFERENCES IN TERMS OF MY STUDY

1. *Objective:* Mueller and Osen were developing estimates of monthly natural dissolved-solids discharge on major rivers throughout the Colorado River Basin. I am developing a method for determining mode of major salt-loading source that could be used throughout the basin, it will not give predictive estimates of natural dissolved-solids discharge. Part of my study will actually make the measurement of salt load in the river and look at the potential for nearby salt in the soils to reach a perennial stream.
2. *GIS application:* This study utilizes statistical analysis, but the benefits of using GIS mapping and analysis here would probably not be as great as from my study,

where I include mapping/characterization of stream-adjacent soils and effects of geomorphic structures on the land.

Nadeau, P.H., 1980, Burial and contact metamorphism in the Mancos shale: Ph.D. dissertation, Dartmouth College, Hanover, New Hampshire, 200 p.

REVIEW

This study was important for me to review, because Nadeau conducted constituent analysis, via X-ray diffraction, of the clays in the Mancos shale. This allowed him to better understand the depositional process and put a timeline on the clay development, via K/Ar method. It helps me to better understand the development history of the Mancos shale and the constituent composition, which will help with the soil textural analysis and understanding of how the clays affect travel of the salts.

RESULTS

Nadeau determined through X-ray diffraction that the dominant clay in the shale is a mixed-layered illite/smectite (40-60% illite). The layers of illite and smectite are interstratified, which Nadeau states is consistent with the concept of burial metamorphism where smectite clays are converted to illite. The results of K/Ar dating of the rock samples indicates that the interstratified illite/smectite formed nearly at the time of deposition. Nadeau takes this information and describes it in terms of other Cretaceous geologic phenomena, including eustatic sea-level, sea-floor spreading, and anoxic events.

DIFFERENCES IN TERMS OF MY STUDY

1. *Focus:* Nadeau study is totally geologic in nature, whereas my focus is a combination of geology, soil science, and hydrology/climate (with a small component vegetation effect). His information is important to my study to better understand how these clays may affect water movement in general and chemical reactions (e.g., cation exchange capacities).
2. *GIS analysis*: If GIS had been better developed in 1980, Nadeau could have used it, but it would have added a lot more work and added to the objectives of his study. As one example, he might have taken the illite/smectite variations areally and mapped them throughout the Mancos shale where he sampled.

Ponce, S.L., II, 1975, Examination of non-point source loading function for the Mancos shale wildlands of the Price River Basin, Utah: Ph.D. dissertation, Department of Civil and Environmental Engineering, Utah State University, 184 p.

REVIEW

Ponce used some of the first funds provided by the BLM to identify salt producing means in 1975 (White, 1977). Ponce used a rainfall simulator set up in the field to study: 1) overland flow on salt movement for selected land types; 2) relative magnitude of surface erosion associated with overland flow and its role in the salt release process; and 3) to develop a non-point source loading function that predicts salt production from diffuse sources. Ponce stated that up until his study, little work had been done concerning the quality of surface runoff from diffuse sources. Most of his literature review was therefore from irrigation studies. The rainfall simulator (a.k.a. Rocky Mountain Infiltometer) measured precipitation, runoff, and sediment produced from a plot – it would retain water so a sample could be collected. Probably the biggest draw back from using the simulator was that you could only do a small plot size with it – therefore, any application of the results to a larger area, might be erroneous. Ponce did soil analysis – saturation extracts and 1:1 extracts. The saturation extracts were analyzed for primary cations, anions, and electrical conductivity.

RESULTS

Ponce did 2 runs on each of 6 small plots. The purpose of the second run was to determine the rate and quantity of salt transport to the surface by evaporation. He plotted electrical conductivity versus time (5 minute intervals) in different soils. He found that undivided Mancos, and Lower or Middle divisions of the Blue Gate members are the major salt contributors. Also, salt concentrations are highest as surface runoff begins, and the salt concentrations in the runoff are fairly low relative to water in the Price River. Soil chemistry showed a thin zone of interaction between soil and overland flow in terms of salt production. Finally, suspended sediment concentration tended to vary directly with salinity concentration of the surface runoff (see Riley RESULTS below). Not sure why, but Ponce said he estimated slope values for the plots – I would think this is something he would want to measure for the development of his non-point source loading equation. Perhaps the plots were so small that it was impossible to determine slope(?) His assumptions for his equation were: 1) uniform coverage by rainfall over the area (this rarely happens with convective storm cells moving over the Plateau); 2) uniform rainfall intensity over the time interval in question; 3) that evaporation, interflow and detention storage are negligible (probably not plausible assumptions, especially for evaporation, and interflow might be dependent on degree of slope); and 4) the mineral salts are homogenously distributed in the soil (any field salinity study by somebody with a chemistry background (see Butler, Duffy and Jurinak, Laronne, and Nadeau reviews above) will tell you there is actually great salt variance that can happen in short distances in soils from the same rock type. So, with very small plot sizes, maybe his assumption on this point is true in a couple of cases, but generally not. It seems clear from reading Ponce's dissertation that he does not have an adequate chemistry background. Therefore regardless of his math skills, he should only undertake this type of study with a chemistry-oriented partner. The outcome of this study was that a very small amount, 0.5 percent, of the total salt mass, which annually leaves the Price River Basin results from direct pickup due to overland flow.

DIFFERENCES IN TERMS OF MY STUDY

1. *Objective:* Ponce created a non-point source loading equation; so his study gathered chemistry data to develop a mathematical relation equation. My study

gathers chemical data, but for statistical correlation analysis, not to develop a mathematical equation.
2. *GIS analysis:* The study is pre-GIS development, but because the plot size were small, I don't think mapping or analysis in GIS would be practical.

Riley, J.P., Israelsen, E.K., McNeill, W.N., and Peckins, B., 1982, Potential of water and salt yields from surface runoff on public lands in the Price River Basin: Report UWRL/P-82/01, Utah Water Research Laboratory, Utah State University, Logan, Utah, 84 p.

REVIEW
Riley and others had an objective to determine how effective structures and land management techniques were at controlling water and salt yields on public lands in the Price River Basin.

RESULTS
Riley determined a number of factors through his study. Some are as follows: Contrary to Ponce's 1975 (above) and White's 1977 (below) studies, Riley found little correlation between TDS and suspended sediment (SS) within any particular subwatershed. There seems to be no correlation between the predominant sulfate anion and salinity. Slope seems to have very little effect on flow, SS, or TDS (though there is a relation between runoff depth and slope). The ratio of the area of saline soil within a subwatershed to the total area of the subwatershed has a direct effect on salinity levels in the surface runoff – it seems to be the most important factor in determining salt load. The effects of contour furrowing are inconclusive because of the sparsity of both before and after treatment data. Also, the effects of chaining on the salinity of the water are difficult to determine due to the lack of data. High salinity in intermittent streams during snowmelt suggests that much of the salt pickup occurs not as overland flow, but from water percolating into the ground and traveling laterally as interflow to the intermittent channels. There are many good findings with this study and an appreciated (by me) willingness to state uncertainties and drawbacks when they were encountered.

DIFFERENCES IN TERMS OF MY STUDY
1. *Objective:* Riley wanted to investigate if land management techniques on public lands were effective, in order to determine this, he and the other authors established many good findings. I think my study will benefit from what Riley learned and I am interested to see if what I find agrees.
2. *GIS analysis:* It is still a bit too early for widespread use of GIS, though I think this is a good study to utilize GIS mapping and analysis on.

Vaill, J.E., and Butler, D.L., 1999, Streamflow and dissolved-solids trends, through 1996, in the Colorado River Basin upstream from Lake Powell – Colorado, Utah, and Wyoming: U.S. Geological Survey Water-Resources Investigations

Report 99-4097, 47 p.

REVIEW

The objective was to conduct trend analysis on discharge and dissolved-solids concentrations and loads, annual and monthly data, from 60 gage stations in the Colorado River Basin above Lake Powell. The period of study is since the 1960s after the last major reservoir interventions were in place.

RESULTS

Generally, significant downward trends in annual dissolved-solids concentrations and loads were identified at 31 of 41 sites. The Yampa River Basin had a significant upward trend.

DIFFERENCES IN TERMS OF MY STUDY

1. *Objective:* (As stated in the Review section above) This is a very useful compilation of data and analysis for any researcher to reference during their own study. The only station on the San Rafael River, San Rafael River near Green River USGS gage 09328500, with long-term chemical data was included as one of the sites in this study.
2. *GIS analysis:* This study is recent enough that it could have benefited from GIS analysis.

Westenburg, C.L., 1995, Dissolved-Solids Contribution to the Colorado River from Public Lands in Southeastern Nevada, through September 1993: U.S. Geological Survey Water-Resources Investigation Report 94-4210, 25 p.

REVIEW

This is one of the few known quantitative studies of salt loading due to ground-water inflow to streams. The USGS has done a couple of other studies that make mention and/or qualitatively state that salt-loading from ground-water inflow to streams on public lands may be a larger factor than has been realized to date. Unfortunately, the areal extent of the study is confined to 9,300 square miles of public lands in southeastern Nevada – small compared to public lands that exist within the Colorado River Basin. The USGS began a 5-year study in 1988 to assess the contribution of dissolved solids from public lands in the Colorado River Basin in SE Nevada. Three watersheds were involved: Muddy R. subbasin (6,200 mi^2), Las Vegas Wash (850 mi^2), and the Virgin R. subbasin (1,100 mi^2). All three are drained by ephemeral tributaries to the Colorado River.

RESULTS

The average annual dissolved-solids discharge from the Muddy R. subbasin to the Colorado R., from October 1988 to September 1993, was about 24,000 tons/year. The average annual dissolved-solids load from the Muddy R. subbasin to the Colorado R. for the same period was about 28,000 tons/year, of which subsurface flow contributed about 86 percent or 24,000 tons/yr. The difference between the dissolved-solids discharge and load of 4,000 tons/yr may be partially due to the salt losses in agriculture areas in the lower parts of the basin, inaccuracies in the methods used to estimate dissolved-solids load, or both. In Las Vegas Wash, from October 1988 to June 1992, the discharge was about 210,000 tons/year, and the load was about 1,300 tons/year for October 1988 through September 1993. Subsurface flow and load for Las Vegas Wash was not split out. Virgin River calculations were an estimated 40 tons/yr of dissolved solids from surface runoff and about 8,700 tons/yr from subsurface load from public lands. In total, the author estimates approximately 38,000 tons of dissolved solids is contributed annually to the Colorado R. Basin by surface runoff and subsurface flow from public lands in Nevada. Westenburg states in his last sentence, "Land-management practices probably would not substantially reduce this contribution."

DIFFERENCES IN TERMS OF MY STUDY

1. *Objective:* Here we have similar objectives, to determine the mode of travel of salt loading to the river. The author states, that even though sufficient data were gathered to provide a basis for more detailed identification of sources, that was not the intent of the study, so more environmental information (e.g., soil surveys and soil sampling) would be needed to locate and quantify areal boundaries of source. The intent of my study is to also do the latter.
2. *GIS analysis:* Westenburg did not use GIS, but since he was not looking at large source areas – his was more of a linear (stream channels/washes) study, GIS might not be that critical to his analysis.

White, R.B., 1977, Salt production from micro-channels in the Price River Basin, Utah: M.S. thesis, Civil and Environmental Engineering, Utah State University, Logan, Utah, 121 p.

REVIEW

White studied the importance of micro-channels in moving salt. The micro-channels develop downslope as runoff is occurring. Ponce, White, and Whitmore (below) all wrote papers at Utah State University about the same time. These efforts were supported by the BLM and were undertaken right after the creation of the 1974 Colorado River Basin Salinity Control Act. Though the 1974 Act was more directed towards on-farm project implementation, EPA was concerned with diffuse sources of salt loading from public lands.

RESULTS

Some of White's conclusions were as follows: 1) The development of micro-channels is extremely variable and the variability increases with the salt content of the system; 2) Within the channel bank, the concentration of salts increases with depth; 3) micro-channels that have silt/clay bottoms experience less seepage; 4) In this area, the Bluegate member of the Mancos shale is the prime source of salt; 5) Gypsum is the main salt with sodium being the most common monovalent cation; and 6) There is a good linear correlation between electrical conductivity and TDS, between suspended solids and TDS, and between EC and suspended solids.

DIFFERENCES IN TERMS OF MY STUDY

1. *Focus:* White is studying a particular feature created by runoff. I am studying the mode of travel of the salt. If the mode of travel is overland flow, then that could lead to the creation of the feature that White investigated.
2. *GIS analysis:* Again, this study was done prior to widespread use of GIS, but it would be an interesting study to apply GIS analysis and mapping.

Whitmore, J.C., 1976, Some aspects of the salinity of Mancos shale and Mancos derived soils: M.S. thesis, Soil Science and Biometeorology, Utah State University, Logan, Utah, 69 p.

REVIEW

This study focused on the kinetics of dissolution of gypsum and calcium carbonate. Whitmore tested the influence of different electrolyte salts at different concentrations upon the solubility of these two minerals. In a lab experiment, a soil columns were leached with deionized water to determine the potential of total salt production.

RESULTS

Whitmore incorrectly refers to concentrations as "loads" (e.g., "Development of water resources in the upper tributary basins has now increased the salt load in the Colorado to 850 ppm, with a projected salt load of 1300 ppm by the year 2000."). It is curious that this mistake was not caught by his chairman or committee. Regardless, there is much important information and the level of knowledge sought and the work effort put into this M.S. thesis is worthy of a PhD dissertation. Whitmore determined that indifferent salts increased the solubility of gypsum and calcium carbonate, and salts with a common ion decreased the solubility of gypsum and calcium carbonate, i.e., evaporite salts can increase the solubility of gypsum due to the indifferent salt effect and ion pair formation. He also confirmed that the salinity of the Mancos derived soils is due to the presence of gypsum and indigenous evaporite salts. One curious finding: "Lithium is the dominate monovalent cation associated with the soils studied in this project. In most cases the lithium concentration is greater than the sodium plus potassium concentrations." It has been stated in other studies that sodium was determined to be the dominant monovalent cation. If it is true that Lithium is the dominant ion, then it might not be a good idea for me to use a lithium salt for my planned tracer injection in the San Rafael River - as it would necessitate a pre-synoptic sampling to get lithium background levels. Whitmore distinguished two diffusion-controlled reactions: a) a fast surface reaction, and b) a slow mineral weathering reaction. He estimates that the fast surface reaction accounts for approximately 80-90 percent of the total salt production. Whitmore deduced from the soil column experiment that a composite surface sample had the potential to produce 3.15 tons of salt per acre-inch (need a clarification on these units), and the salt accounted for 1.89 percent of the soil's total mass.

DIFFERENCES IN TERMS OF MY STUDY

1. *Focus:* Whitmore studied the kinetics of gypsum and calcium carbonate dissolution potentials, as such, he provided important insight into the chemical behavior of salt. For my study, the mode of travel is largely dependent on these microscopic reactions and kinetics. My study is just the larger view, with the additional geomorphic and climatic factors included.
2. *GIS analysis:* Much of Whitmore's work is laboratory experiments and mathematical 'crunching' of the chemical reactions, so in this respect, GIS analysis is probably not as applicable.

Williams, B.G., and Braunach, M., 1983, The detection of subsurface salinity within the Northern Slopes region of Victoria, Australia: *In* French, R.H. (ed.), Salinity in watercourses and reservoirs, Proceedings of the 1983 International Symposium on State-of-the-Art Control of Salinity, July 13-15, Salt Lake City, Utah, Butterworth Publishers, Stoneham, MA, pp. 515-524.

REVIEW

This last selected review is outside the Colorado Plateau. Much salinity work has been done in Australia and we can benefit from their gained knowledge of salt-loading systems. Williams and Braunach discuss the importance of discerning subsurface saline material and ground water, while keeping the assessment costs down. They point out that logging surveys in monitoring wells, even though they give excellent detailed information are isolated (since salt concentrations in the soil can greatly vary over short distances) expensive, time consuming, and it is difficult to know where to drill the holes. Exploration drill hole surveys are also environmentally unsound (my opinion). Electromagnetic induction surveys (EM) are cheaper, provide better coverage and thus become a better means for determining ground salinity. It is true the EM instruments have limitations and can be 'confounded' when recording measurements – so in this regard the reliability of the data probably isn't as good as data recorded from a logged hole. However, in the larger perspective and for the aforementioned reasons, one should still choose an EM survey. Williams and Braunach paper describes the application of the EM technique across a transect in the lower Northern Slopes area of Victoria. Their purpose in conducting this survey was to determine the magnitude and spatial variability of apparent electrical conductivity (a measure of salinity) and relate the magnitude and spatial variability to the underlying geology and known areas of secondary salinization.

RESULTS

The survey confirmed the wide variability in the distribution of saline materials within the major geological formations. They also calculated from the survey results that approximately 300 km of the 500 km transect have a potential for secondary salinization should ground water travel through these materials. EM surveys should have some borehole sample controls, to help calibrate the instrument data.

DIFFERENCES IN TERMS OF MY STUDY

1. *Objective:* Williams and Braunach discussed the use of a tool (electromagnetic induction meters) to locate areas and determine spatial variability of saline soils (possibly not yet exhibiting salinity at the surface – subsurface occurrence). I will also use this tool and it is a very important part of my study to help determine the mode and source of salt loading in the San Rafael River, Utah.
2. *GIS analysis:* This would be a good study for GIS mapping and analysis.